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Cadmium in West Germany: how much do we know about stocks and flows?

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Kiel Working Paper No. 494

Cadmium in West Germany
How Much Do We Know About Stocks and Flows ?

by Gernot Klepper and Peter Michaelis
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1. Introduction*

Cadmium as a toxic material and as such being a threat to mankind and the environment has become well-known through the so-called Itai-Itai-Disease which occurred in Japan in the 1960's. It was induced by heavy cadmium contamination of rivers and consequently of rice. Since then many toxicological studies have revealed that cadmium belongs to the most toxic heavy metals and that it is particularly dangerous for living organisms since it accumulates slowly in the body revealing its toxic effect only with a long time lag.

The world production and use of cadmium has drastically increased during this century from about 100 t per year in the 1920's to about 20.000 t in the 1970's and 1980's (Ewers, 1990). Whereas cadmium can be found in the earth's crust only in low concentrations and thus poses no danger, it develops its toxicity only in concentrated forms. Therefore the production and use of such large amounts produces considerable health hazards, especially since the increasing stock of cadmium in the environment, i.e. in soils and sediments, does not quickly disappear from the human environment.

This increasing potential health hazard has led the Sachverständigenrat für Umweltfragen (1987) in Germany to demand a reduction in the use of cadmium and in the exposition of humans to cadmium through air, water and food. Similarly, the Third International Conference on the Protection of the North Sea asks for reductions of inputs of cadmium into the North Sea - among other substances - between 1985 and 1995 by at least 70 % (Third International Conference 1990). These demands raise a number of questions:

* We like to thank Gudrun Mahlau for excellent research assistance. We are also indebted to the numerous institutions and firms which have supplied us with valuable information and data.

- What is the quantitative flow of cadmium in the economy?
- How does it interact with the existing stock?
- Which sectors contribute to the accumulation of the stock of cadmium in the economy and in the environment?
- Which sectors emit cadmium in the different environmental media?
- How did these emissions evolve over time and what is their likely future path?
- What is the potential for reducing the flow of cadmium in the economy?
- What is the technological potential for reducing cadmium emissions into media which then impose health hazards, directly or through the food chain?
- What are the economic costs of achieving such reductions?

Surely, these questions can not be answered at once. This paper is a first step in this direction by collecting all available information about the material flow of cadmium in West Germany. Such an account is rather speculative since the flows are not systematically registered. In addition, it is also complicated through interactions of flows of newly produced cadmium with recycled cadmium from the already existing stock. Economic activities therefore include newly produced and recycled cadmium as intentional inputs but also cadmium as a contamination of new raw materials as well as of recycled products. All of these influences are of particular importance for the prediction of cadmium emissions in the future.

The first part of the paper presents estimates of the yearly addition of cadmium to the existing stock in West Germany and of the flow of cadmium through the economy. Further, the amount of cadmium is assessed which remains in the economy in the form of products containing cadmium. This stock of cadmium will - with different time lags - be emitted into the

environment or be reprocessed in the industry. The next two parts estimate the development of cadmium emissions into the water and the air on a sectoral level. They also present some information about the causes for these developments and - as far as this is possible - some predictions about future emissions. The paper closes with a summary of the findings and a discussion of strategies and potentials for reducing the threat of cadmium for human beings and the environment in general.

2. Cadmium flows in Germany

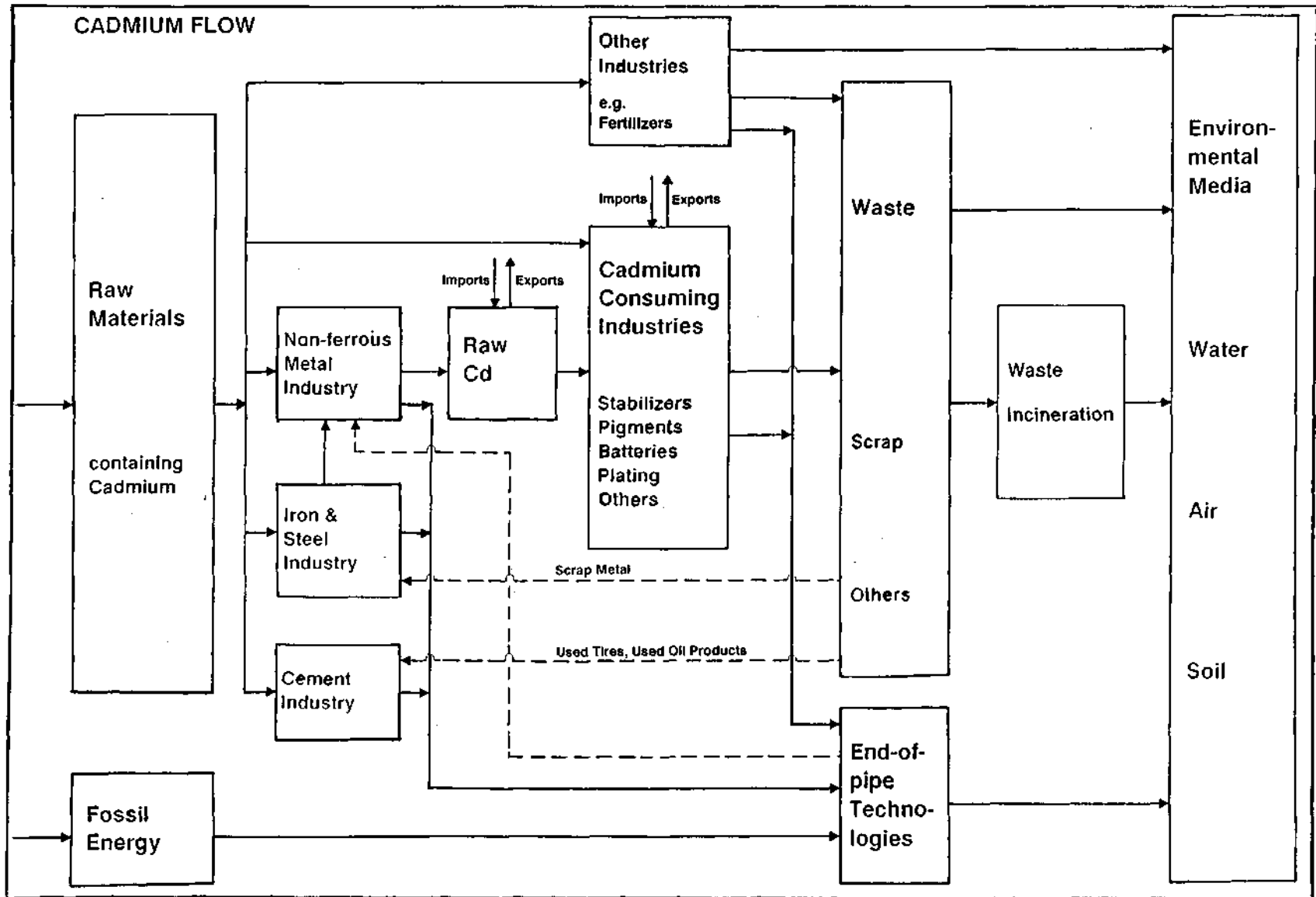
Cadmium is a relatively rare element which occurs in the earth in low concentrations thus making mining not economical. Cadmium is produced as a byproduct during processing of zinc concentrates which normally contain 0.1-0.3% of cadmium, although the concentration in some instances can be as high as 1% (Suess et al. 1985). In addition to the intentional production of cadmium as a raw material it also enters the environment and the economy unintentionally as a contamination of fuels, iron ore and other materials.

The main problem with cadmium is its ability to accumulate in living organisms and thus to create health risks in the long-run. Therefore, it would be desirable to illustrate the development of the stock of cadmium in specific environmental media and in products. Unfortunately, such a cadmium balance is impossible to construct given the information which is available at the moment. The only feasible approach consists of a detailed enumeration of sectoral flows of cadmium. Due to missing legal requirements for data collection on the use and emissions of cadmium even this approach is highly speculative.

Figure 2.1 illustrates the most important streams of cadmium. The accumulation of cadmium in the human environment comes intentionally through the non-ferrous metal industry which produces raw cadmium for later use in the manufacturing industry and unintentionally through predominantly the iron & steel and the cement industry but also through the burning of fossil fuels - mostly coal - and through the production and use of fertilizers. This new flow turns into waste which is emitted into air, water or soil and into products containing cadmium.

The flow chart, however, does not illustrate the flow in one particular period. It encompasses several periods and also includes the effects of the existing stock of cadmium. The first effect is due to the fact that cadmium in products is

Figure 2.1



added to the existing stock and remains in this form for possibly decades - an example would be plastic window frames. Hence the transformation of goods into waste and the emission into environmental media may take place many periods after the production of cadmium, but cadmium may also be emitted immediately after use - as in the case of fossil fuels. For a quantitative assessment of emissions of cadmium into the environment the input of new cadmium into the economic process may not be very important. Beyond that, even if there were no new cadmium coming into the system, the existing stocks would for quite some time still induce uncontrollable flows and emissions.

The influence of the already existing stock of cadmium on flows is manifold. An important controlled flow goes from filters of incinerators back to the non-ferrous metal industry where some of the dust is recycled. Uncontrolled additions to the flow of cadmium experience the iron & steel industry through the contamination of scrap metal with cadmium and the cement industry. Another important addition to flows which is not shown in Figure 1 is the contamination of soils which enter the food chain. The arrows do not contain numbers about the volume of cadmium flows for several reasons. Some arrows can not be quantitatively assessed due to a lack of data and others are subject to such large errors that we prefer to discuss these numbers in the following chapters.

2.1 Production of Cadmium

The intentional production of cadmium takes place as a joint product of zinc processing in which it is a trace element. Almost all cadmium is extracted from zinc ore and more than 98 % of the extracted material is used as an input in production whereas the rest is emitted. About 3.2 kg of cadmium per ton of zinc can be produced (Brahms et al., 1989, p. 148).

Table 2.1: Cadmium Production in West Germany (t/a)

	1981	1982	1983	1984	1985	1986
Primary production	1323	1293	1191	1242	1305	1359
Secondary production	231	141	71	226	185	202
Total	1554	1434	1262	1468	1590	1561

Source: Böhm/Schäfers (1990, p. 6-7).

Table 2.1 summarizes the production of cadmium in West Germany. Primary production from zinc processing dominates the production through secondary processing of used metals. The total cadmium production remained approximately constant in the first half of the 1980's.

For an assessment of cadmium flows in Germany not only the production of cadmium but the inflow and outflow of cadmium through international trade must be taken into account. Balzer/Rauhut 1987 estimate these relations in a "Cadmium Balance". It incorporates all inputs of cadmium from abroad in the form of raw materials, e.g. zinc, of raw cadmium, or of cadmium contained in products. On the other side, exports of cadmium and cadmium containing products are also taken into account. For 1986 531 t of cadmium metal have been imported and 438 t exported resulting in 93 t net imports. In the same year 985 t of cadmium contained in products was imported compared to 1314 t of exported cadmium, thus resulting in net outflow of cadmium in products of 329 t. The overall trade effect is a net outflow of cadmium of 236 t in 1986. Hence of the cadmium production amounting to 1561 t about 1325 t did remain in Germany in 1986.

2.2 Inadvertant Input of Cadmium

In addition to the intentional use of cadmium in production it also enters the environment as a trace element in other economic activities. Especially the burning of fossil fuels, the manufacturing of iron and steel and cement production are the main contributors.

Cadmium is a trace element in coal and oil with widely varying contents - between 0.1 and 10.0 ppm (for details see Table 4.2 in chapter 4). Since large amounts of fossil fuels are burned a considerable input of cadmium into the environment can take place. Given the input of fossil fuels, Böhm/Schäfers (1990, p.9) report estimates from the Umweltbundesamt according to which cadmium input is 98 t from hard coal, 11 t from brown coal, and about 1 t from oil.

The cadmium input of the iron and steel industry comes to a small extent from trace elements in iron ore. The more important input, however, is the cadmium content of scrap metals which are recycled in the production of iron and steel. In this case it becomes very difficult to determine the flow of cadmium since this flow depends on the stock of cadmium in scrap metal which was produced some decades earlier (see Rat von Sachverständigen für Umweltfragen, 1991, p. 231). The situation is further complicated by the fact that the iron and steel industry gives filter dust and sewage sludge with high heavy metal contents to the non-ferrous metal industry for recycling. Non-recyclable parts often are returned into the smelters. It is likely that more than 100 t of cadmium which belong to the already existing stock are again processed.

The cadmium load of the cement industry also is due to the already existing stock of cadmium. In this industry a consi-

derable part of the energy input is taken from used tires¹ and used oil products having high cadmium contents. A similar source of cadmium is the waste incineration for which cadmium inputs are unknown, however. Although these processes do not add to the existing stock of cadmium in the environment, they reactivate cadmium and turn it into a potential emission source into air and water.

Combining in quantitative terms all sources of cadmium which flow through the economy is practically impossible. Some rough numbers must suffice for indicating the dimensions. As far as the flow of cadmium is concerned which is added to the already existing stock every year in the form of cadmium containing products or in the form of emissions, the dimension is around 1200 t per year. In terms of environmental effects, however, not the stock but the flow of cadmium in production or consumption processes is relevant since it provides the potential for emissions into the environment. Rauhut (1990) estimates a throughput of 3077 t in 1986 in West Germany which exceeds the addition to the stock by a factor of more than two. It remains to emphasize that these numbers are highly speculative.

2.3 The Use of Cadmium in Production

The flow of cadmium in one time period ends in essentially three possible states. It leaves the country as exports either directly or incorporated in products. The second possibility is the transformation of cadmium into products which remain in Germany; and finally, cadmium can be emitted into the environment during the production or during the consumption of the product. The incorporation of cadmium into products thus only extends the time lag after which the cadmium becomes a potential source of emission. Whereas the actual emissions into wa-

¹ In 1987 the German cement industry did burn about 157.000 t of used tires amounting to 39 % of all used tires (Rat von Sachverständigen für Umweltfragen, 1991, p. 190).

ter and air are discussed in the later chapters, here the conversion of cadmium into products is discussed. The amount of cadmium in these products is an important determinant of emissions in later years where these products are returned to production processes through recycling or are disposed off through waste incineration or dumping.

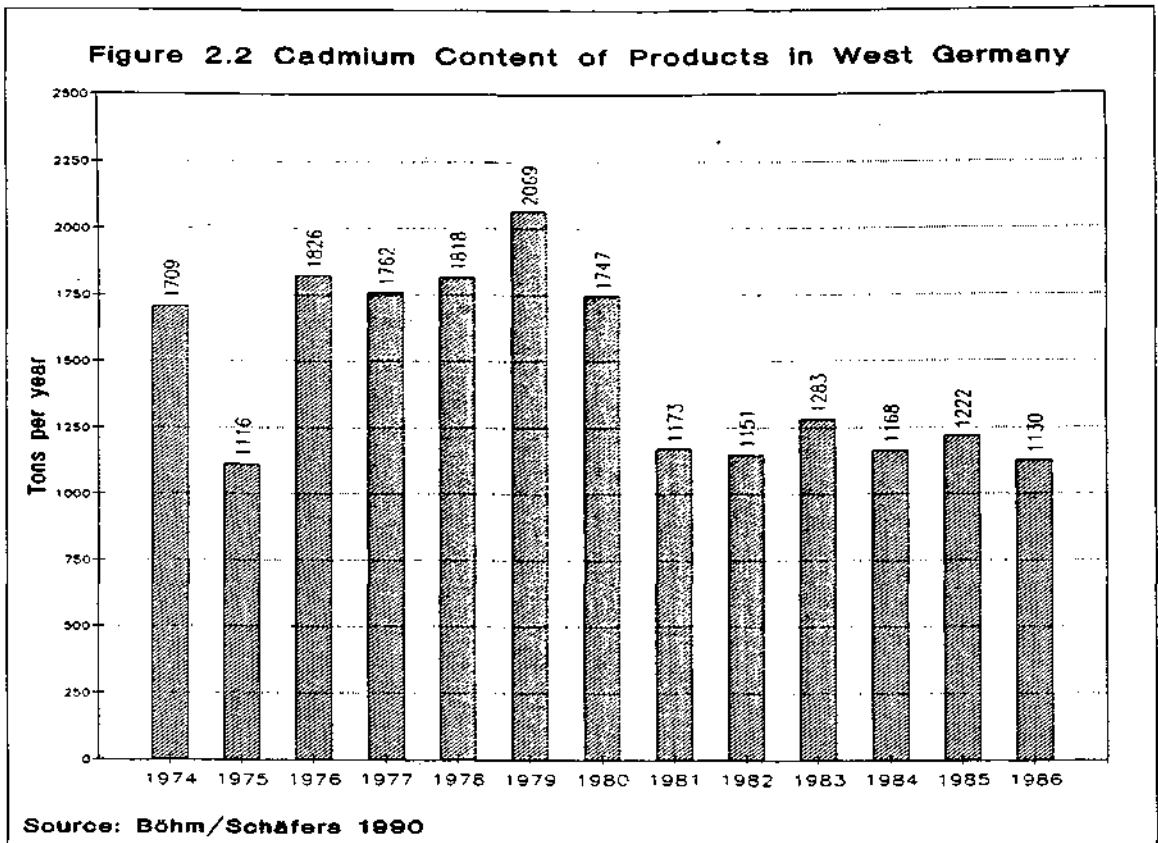


Figure 2.2 shows the development of cadmium in products which enters German markets between 1974 and 1986. The level of roughly 1700 t to 1800 t per year in the seventies has dropped to between 1100 t and 1200 t in the eighties, however without a continuing falling trend in the last years for which data are available. A look at the development by product groups reveals that there are different trends at work which accidentally level out in the eighties (see Table 2.2).

The most important developments can be observed for batteries and plating. In the market for batteries the Nickel/cadmium batteries achieve increasing market shares. Consequently the amount of cadmium contained in batteries has doubled between the mid-seventies and mid-eighties from 150 t to about 300 t per year.

Table 2.2: Cadmium in Products.

	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
Stabilizers	248	207	349	366	384	522	490	368	328	317	278	296	289
Pigments	771	424	664	572	619	753	548	291	317	293	364	434	363
Batteries	150	150	253	238	192	213	238	280	255	357	300	310	308
Plating	354	196	420	397	382	319	266	160	180	200	167	118	122
Cadmium Compounds	25	13	27	91	108	142	126	20	20	37	33	39	19
Alloys	87	75	52	47	63	44	31	31	29	28	22	21	23
Glass	22	13	12	15	13	15	14	12	10	11	4	4	6
Rectifiers	24	16	19	6	6	21	8	3	1	1			
Others	28	22	30	30	51	40	26	8	11	39			

Source: Böhm/Schäfers (1990).

Some authors guess that the number may be as high as 400 t because of insufficient accounting of battery imports (Böhm/Tötsch, 1989, p. 89). Since the importance of Ni/Cd-batteries is still rising, they will in the future become the most important medium in which the stock of cadmium is stored.

The opposite development can be observed in plating. The use of cadmium has dropped from 420 t in 1976 to around 120 t in 1985/86. This process is mostly due to the reduction of cadmium-galvanized steels in the automobile industry. Further reductions may be possible if similar changes in technology will be introduced in the aerospace and defense industry which

consume a large part of such metals (Böhm/Schäfers, 1990, p. 38-39).

The development in the other product categories is mixed. Pigments which used to make up for almost half of all cadmium in products have fallen to around 30%. After a considerable reduction there has been an increase in the last few years which may be due to increased production of plastic materials. For stabilizers a falling trend can also not be clearly identified. A more detailed analysis of technical potentials for reducing cadmium in these products is in Böhm/Schäfers (1990) and Böhm/Tötsch (1989).

3. Aqueous cadmium emissions

According to the usual classification scheme aqueous cadmium emissions can be grouped into three different categories, based on their origin (cf. e.g. Deutsche Kommission zur Reinhaltung des Rheins, 1989, p.8):

Categorie 1: emissions originating from industrial sources which are directly discharged to surface waters,

Categorie 2: emissions originating from municipal waste water treatment plants, and

Categorie 3: emissions originating from diffuse (non-point) sources, like e.g. atmospheric deposition and inputs of agrochemicals.

However, these classification is not completely consistent with the methods employed to quantify cadmium emissions from industrial activities. Usually, these emissions are not directly measured at the 'end of the pipe' but estimated by applying emission factors (e.g. gram of aqueous cd emissions per ton of output) to numbers regarding the quantity of output produced or the quantity of cadmium used in specific processes. These emission factors usually account not only for the direct discharge to surface waters but, where appropriate, also for the indirect discharge via municipal treatment plants. Therefore, the available estimates of aqueous cadmium emissions from industrial activities include not only direct discharges (categorie 1) but also those parts of the emissions from municipal treatment plants (categorie 2) which can be traced back to industrial activities. However, this categorization problem which may be crucial for pollutants other than cadmium is easy to solve in the case at hand. Due to the fields of application of cadmium (batteries, stabilizers, plating and pigments) it can be claimed that the consumption of cadmium containing products does not lead to a significant

cadmium input into the waste water¹ of private households'. Hence, it seems to be reasonable to assume that the sources of the cadmium load of municipal waste water are almost exclusively industrial activities. This implies that the available estimates of industrial cadmium emissions (see Section 3.1) completely cover both direct emissions (categorie 1) and emissions from waste water treatment plants (categorie 2). In the following we refer to these emissions as 'point source emissions' because in both cases the discharge to surface waters occurs at one specific point in space.

3.1 Aqueous emissions from point sources

There exists a lot of engineering literature on aqueous cadmium emissions caused by specific production processes (see e.g. Elgersma et al., 1991, pp.93-99.). However, up to now only few attempts have been made to estimate total aqueous point source emissions by countries and sectors. Concerning the FRG only two comprehensive studies on this issue are available.²

The first study - hereafter cited as ERL-Report (1990) - was undertaken during 1989 by Environmental Resource Limited (ERL) on behalf of the Commission of the European Communities (Directorate General for Environment, Consumer Protection and Nuclear Safety - DG XI). The aim of this study was the quantification of cadmium emissions to air, water and land on a

¹ The only exception may be the use of toilet paper manufactured from waste paper. However, as empirical studies indicate, the cadmium content of toilet paper manufactured from waste paper ranges only from 0.03 to 0.20 mg Cd per kg (cf. Brahms et al., 1989, p.224). Accounting for a total consumption of about 300.000 tons of toilet paper per year (cf. e.g. Heinstejn/Seeberger, 1986), this is clearly not enough to contribute significantly to the municipal waste water's cadmium load.

² Beside these two studies there are various other specific data on aqueous cd-emissions in the FRG available from the literature. However, these figures are not broken down by sectors or activities and they partially exhibit a considerable degree of divergence.

source by source, country by country basis for each of the 12 Member States. However, as will be seen below, the results for the FRG presented in the ERL-Report (1990) seem to be highly unreliable due to methodological shortcomings.

The second study - hereafter cited as Elgersma et al. (1991) - was undertaken by the International Institute for Applied System Analysis (IIASA). This study focuses exclusively on aqueous cadmium emissions in the Rhine River Basin, and therefore total German cadmium emissions are not covered. However, the restriction to the Rhine River Basin facilitated a more detailed study of the individual emission sources and for that reason the results presented by Elgersma et al. (1991) seem to be much more reliable than the figures published in the ERL-Report (1990).

Table 3.1: Estimates of aqueous cd-emissions in the FRG by activities (source: ERL-Report, 1990, p.iv).

Activity	Aqueous emissions (tons/year)	Share on ECE- wide emissions	Year under review
Iron and Steel prod.	6.3	29.7%	1987
Zinc refining	5.1	29.5%	1985
Lead refining	2.5	25.0%	1985
Battery manuf.	1.1	34.4%	1988
Pigment manuf.	6.0	28.6%	1988
Stabilizer manuf.	0.63	63.0%	1986
Cadmium Plating	4.6	23.4%	1987
Incineration of sewage sludge	0.1	50.0%	1983
Total	26.3	21.2%	various

Source: ERL-Report (1990, p.iv).

Table 3.1 contains the estimates of aqueous cadmium emissions in the FRG by activities as published in the ERL-Report (1990).³ The first row describes cd-emissions in tons per year, the second row indicates the percentage contribution of Germany to the estimated total EC-wide cadmium emissions caused by the respective activity, and the third row indicates the year under review.

Table 3.1 suggests that the FRG is responsible for more than one fifth of the overall aqueous cadmium emissions in the ECE. In particular, the German iron and steel industry as well as zinc refining and pigment and plate manufacturing seem to contribute considerable to total cadmium emissions. However, as will be seen from a comparison with the study by Elgersms et. al (1991), it must be suspected that the figures published in the ERL-Report (1990) highly overestimate the real aqueous cadmium emissions caused by industrial activities in the FRG.

Table 3.2 contains the estimates of annual aqueous cd-emissions from industrial point sources in the German part of the Rhine River basin for the year 1988 and for the time periods of 1978 to 1982 and 1983 to 1987 as published by Elgersma et al. (1991). Although this study covers only the Rhine River basin and the break down by activities differs slightly from the one employed by the ERL-Report (1990), a comparison of tables 3.1 and 3.2 clearly indicates that the results of the two studies are not in line with each other. In particular, the following inconsistencies stand out:

- The ERL-Report (1990) estimates 5.1 tons of cd-emissions from zinc refining in 1985, whilst the respective figure by Elgersma et. al. (1991) is only 0.5 tons per year for the period of 1983 - 1987. Since almost 50% of total German zinc

³ Beside the activities mentioned in table 3.1, the authors of the ERL-Report consider also the following activities to contribute significantly to the aqueous emissions of cadmium in the FRG: non-ferrous mining, refining of copper, CDO-production and alloy manufacturing. However, due to lack of data, no attempts have been made to estimate these figures.

Table 3.2: Estimates of aqueous point source cd-emissions in the Rhine River basin by countries and activities

Country/Activity	Aqueous cd emissions (tons/year) in period:			
	1978-1982	1983-1984	1985-1987	1988
<i>- Federal Republic of Germany -</i>				
Non-ferrous mining	0.1	0.1	0.1	.
Iron and Steel prod.	9.9	4.2	4.2	1.1
Primary zinc/lead industry	1.0	0.5	0.5	0.1
Secondary zinc industry	50.0	25.0	0.0	0.0
Secondary lead industry	0.6	0.6	0.6	0.6
Battery manufacturing	0.9-1.3	0.5-0.7	0.5-0.7	0.3
Pigment manufacturing	1.3	0.3	0.3	0.2
Stabilizer manufacturing	0.6-1.4	0.4-0.9	0.4-0.9	0.0
Cadmium plating	2.0-4.4	0.1-0.7	0.1-0.7	0.1
Coke production	3.1	0.5	0.5	0.5
Total FRG	69.5-73.1	32.2-33.5	7.2-8.5	2.9
<i>- France -</i>				
Iron and Steel	5.5	2.4	2.4	0.6
Phosphoric acid manuf.	1.9	< 1.9	< 1.9	< 1.3
Other activities	0.9	0.9	0.9	0.5
Total France	8.3	3.3-5.2	3.3-5.2	1.1-2.4
<i>- Netherlands -</i>				
Phosphoric acid manuf.	13.7	13.7	13.7	9.0
Other activities	--	--	--	--
Total Netherlands	13.7	13.7	13.7	9.0

Source: Elgersma et al. (1991).

production in 1985 was located in the Rhine river basin,⁴ there is a remarkable gap between these estimates.

- In the case of pigment manufacturing a cross-checking between the results of the two studies is of particular ease because there are only three main cadmium pigment producers in the FRG which are all located in the Rhine River basin (Besigheim, Bonn, Leverkusen).⁵ Therefore, the estimates presented in both studies should be almost congruent. However, as can be seen from table 3.1 and 3.2, the figure published by the ERL-Report (1990) - 6 tons/year - and the figure published by Elgersma et al. (1991) - 0.2 tons/year - differ by a factor of 30.
- Finally, a large gap between the estimates concerning the aqueous cd-emissions from plating attracts attention. For 1987 the authors of the ERL-Report (1990) estimates 4.6 tons of aqueous cd-emissions from plating, whilst the respective figures estimated by Elgersma et. al. (1991) are only 0.1-0.7 tons per year for the period of 1985-1987 and 0.1 tons for the year 1988. Since in the FRG appr. 75% of all cd-plating activities take place in the Rhine River basin (see Elgersma et al., 1991, p. 65), there is a remarkable inconsistency between these two estimates.

What are the reasons of these large discrepancies? Obviously, the most crucial factor in estimating emissions from industrial point sources is the determination of appropriate emission factors which relate the amount of cd-emissions to the amount of cd used in the process or to the amount of goods produced. Table 3.3 summarizes the emission factors employed by Elgersma et al. (1991) and by the authors of the ERL-Report (1990). As can be seen from this table there are enormous

⁴ According to Elgersma et al. (1991, p. 38) the annual zinc production in the Rhine River basin amounted to appr. 170,000 tons in the period of 1983-1987, whilst the total German zinc production amounted to appr. 366,000 tons in the year 1985.

⁵ Note, that the producer located at Leverkusen left the market in 1988 (see Elgersma et al., 1991, pp.45-46).

discrepancies between the respective figures. The primary reason for these discrepancies comes from the fact that the technological conditions which determine the respective emission factors often vary from country to country and even from source to source. Therefore, in principle it would be necessary to obtain individual emission factors for each single emission source.

Table 3.3: Comparison of emission coefficients used by Elgersma et al. (1991) and ERL-Report (1990).

Activity	Elgersma et al.		ERL-Report
	1985-1987	1988	
Non-ferrous mining ¹	0.10	0.10	-
Iron and steel production ²			
- Basic oxygen steel	0.20	0.05	0.18
- Electric arc steel	0.20	0.05	0.14
Zinc refining ³			
- thermal process	5.00	0.50	26.00
- electrolytic process	0.10	0.10	5.70
Lead refining ⁴			
- primary production	5.00	0.50	8.40
- secondary production	6.20	6.20	6.16
Battery manufacturing ⁵			
- pocket plate	1.50	1.00	3.00
- sintered plate	2.00 - 3.00	1.00	0.50
Pigment manufacturing ⁵	0.50	0.30	15.20
Stabilizer manufacturing ⁵	0.60	0.40	1.81
Cadmium plating ⁵	1.00 - 6.00	0.30	23.00

Dimension of emission factors: ¹ g Cd/t Zn,Pb-concentr.; ² g Cd/t steel; ³ g Cd/ton Zn; ⁴ g Cd/ton Pb; ⁵ kg Cd/ton Cd used in process.

Source: Elgersma et al. (1991) and ERL-Report (1990).

Concerning this problem the authors of the ERL-Report (1990, p.ii) complain that they "... were largely unable to obtain data concerning emission control technologies in operation in different Member States. The effect of this is that emission factors that were derived from a particular plant, or data from a particular country, have been applied uniformly to all EC States."⁶ In contrast to this rather loose-knit approach Elgersma et al. (1990) succeeded in obtaining emission factors on a real source-by-source base for almost each of the considered activities in the Rhine River basin. Therefore, the emission factors employed by Elgersma et al. (1990) seem to be much more reliable concerning the German situation than the figures used in the ERL-Report (1990).⁷

A second source of divergencies between the employed emission factors is due to the fact that the authors of the ERL-Report in some cases do not account for the effects of waste water treatment activities. For instance in the case of pigment manufacturing they claim that 6% of the cadmium input is lost in production, of which 4,47% is reclaimed in the plant, 1.4% is emitted to municipal waste water treatment plants and 0.12% is directly discharged to water. From this partitioning, which seems to be undisputed in the literature and which is also used by Elgersma et al. (1991), they conclude that total aqueous cd emissions equal 1.52% of cd input, i.e. 15.2 kg cd per ton of cd used in process. This conclusion, however, is wrong because it does not account for the effects of wastewater treatment activities. As Elgersma et al. (1991, p.46-47) point out, the cd removal factor of municipal treatment plants equals 40-60%, i.e. roughly half of the waste water's cd-load is filtered out and only the remaining partition is discharged

⁶ For instance the emission factor used to calculate aqueous cd-emission from zinc refining is solely based on information supplied by the Belgian non-ferrous metal industry (see ERL-Report, 1990, Annex A24).

⁷ However, in favour of the authors of the ERL-Report (1990) it should be born in mind that the scope of the study by Elgersma et al. (1991) is limited to the Rhine river basin and hence the number of emission sources to be considered is much smaller.

to surface waters. Moreover, in the FRG cd pigments are only produced in large chemical plants which are equipped with own waste water treatment facilities. According to Elgersma et al. (1991, p.47) the cd removal factor of this type of facility usually amounts to 90% and more. Hence, in order to obtain a reliable emission factor the above mentioned partitions of cd lost in process have to be corrected by the removal factors of the respective treatment facilities.⁸ This recalculation leads to the emission factor employed by Elgersma et al. (1991).

To summarize: The results of the ERL-Report (1990) concerning aqueous cd emissions in the FRG are unsatisfactory due to the employment of unsuitable emission factors. On the contrary, the estimates published by Elgersma et al. (1991) seem to be much more reliable, but they cover only the Rhine river basin. In view of this situation, it seems to be the most sensible strategy to use the figures published by Elgersma et al. (1991) for estimating the total German aqueous cd emissions (see table 3.4). For this purpose we assume that the technological standards prevailing in the German part of the Rhine River basin are representative for the respective industries all over the FRG. Under this assumption the emission factors used by Elgersma et al. (1991) can be applied to the respective production or input data for the FRG as a whole.

Obviously, the quality of our estimates as presented in table 3.4 crucially depends on whether the assumption that the emission coefficients obtained in the German part of the Rhine River basin are reliable proxies for the technological standards in the FRG as a whole is applicable. We have not found evidence speaking against this assumption. In particular, there are no reasons to believe in regionally different patterns of technological development (i.e. the diffusion of innovations etc.) since there are uniform economical and legal conditions in the whole FRG as well as in the German part of the Rhine Ri-

⁸ A similar objection has to be made concerning the emission factor used in the ERL-Report (1990) to calculate aqueous cd-emission from plating.

Table 3.4: Projection of aqueous cd-emissions in the FRG by activities 1988.

Activity	Emission factor	Output/Input quantity	Aqueous cd emissions
<i>Cd as inadvertent input in production process:</i>			
Non-ferrous mining ¹	1.00 g/t	93,500 t	0.09 t
Iron and Steel ² prod.	0.05 g/t	35,508 kt	1.78 t
Coke production ³	0.03 g/t	18,274 kt	0.55 t
Thermal zinc refining ⁴	0.50 g/t	81,000 t	0.04 t
Electrolytic zinc refining ⁴	0.10 g/t	271,000 t	0.03 t
Primary lead production ⁵	0.50 g/t	185,600 t	0.09 t
Secondary lead production ⁵	6.20 g/t	168,500 t	1.04 t
<i>Cd as intentional input in production process:</i>			
Battery manufacturing ⁶	1.00 kg/t	292 t (1987)	0.29 t
Pigment manufacturing ⁶	0.30 kg/t	393 t	0.12 t
Stabilizer manufacturing ⁶	0.40 kg/t	270 t (1987)	0.11 t
Cadmium plating ⁶	0.30 kg/t	72 t	0.02 t
Total aqueous emissions from inadvertent use of cd:			3.62 t
Total aqueous emissions from intentional use of cd:			0.54 t
Grand total			4.16 t
<i>Dimension of emission factors: ¹ g Cd/t Zn,Pb-concentr.; ² g Cd/t steel; ³ g Cd/t coke; ⁴ g Cd/t Zn; ⁵ g Cd/t Pb; ⁶ kg Cd/t Cd used in process.</i>			

Source: Own calculations; based on: Böhm/Schäfers (1990), Elgersma et al. (1991), Metallgesellschaft (1989) and Statistisches Bundesamt (1990a).

ver basin. Moreover, the contribution of the Rhine River basin's industry to the activities under question exceeds 50 per cent (measured as the share on total output or total cd use) in virtually all cases. And finally, the calculated figures are roughly in line with estimates of the German "Umweltbundesamt" according to which total cadmium emissions to surface waters in 1986 are be 7-9 tons per year⁹ (see Böhm/Schäfers, 1990, p.12), and also with Rauhut (1990) who asserts for the same year that aqueous cd emissions caused by the industrial use of cadmium amounted to 1.6 tons (see Rauhut, 1990).

From the above discussion it seems to be justified to claim that our estimates presented in table 3.4 are considerably more reliable than the respective figures published in the ERL-Report (1990). A comparison of tables 1 and 4 suggests that the authors of the ERL-Report overestimate aqueous point source emissions of cd in the FRG by a factor of more than six. Particularly, aqueous cd emissions actually caused by zinc refining, pigment manufacturing and cadmium plating turned out to be substantially smaller than asserted in the ERL-Report (1990). Hence, the ERL-Reports' (1990) result that the FRG contributes with 26.3 tons/year for appr. 21.2% of total aqueous point source emissions in the EC seems to be untenable.

Basically, there are three messages which can be drawn from the data discussed hitherto:

- 1) Due to substitution processes and improvements of emission control technologies aqueous cd emissions from industrial point sources in the FRG have decreased enormously over the last decade: In contrast to the beginning of the eighties, when aqueous point source emissions of cd amounted to appr. 70 tons/year alone in the Rhine River basin, emissions came

⁹ This number, which is not further broken down by sectors or activities, includes emissions from point sources as well as from diffuse sources.

down until 1988 to appr. 2.9 tons/year in the Rhine River basin and appr. 4.2 tons/year all over the FRG. This implies that aqueous point source emissions decreased by a factor of more than 20 within a timespan of less than ten years.

- 2) The intentional employment of cadmium as productive input (plating; manufacturing of batteries, pigments, stabilizers) accounts for only 13% of total aqueous point source emissions, whilst the remaining 87% are due to the inadvertent entry of cd into the production process. Within the latter category there are three activities which cause more than 90% of emissions: iron and steel production (49%), secondary lead production (29%) and coke production (15%).
- 3) The partition of emissions suggests that measures aiming at reducing aqueous point source emissions of cadmium should primarily try to come to grips with the problem of the inadvertent entry of cadmium into the production process. However, as will be seen in Section 4, this problem is partially (and with a considerably time-lag) caused by the use of cadmium as productive input.

3.1 Aqueous emissions from non-point sources

Up to now, the discussion of aqueous cadmium emissions has been exclusively concentrated on industrial point sources. This, however, is not the full story. As Stigliani (1990, p. 334) emphasizes, aqueous emissions from diffuse sources are *"... a significant fraction of total emissions of environmental harmful chemicals, and it appears likely they will become even more important as industrial point sources are increasingly regulated."* For instance in the case of the Rhine River basin it is estimated that in 1985 about 68% of the discharge of heavy metals and organic chemicals stemmed from diffuse sources, and projections indicate that the share of diffuse

sources will increase to more than 80% until 1995 (Stigliani, 1990, p. 333).

From an empirical point of view the most striking distinction between point sources and diffuse sources is the fact that emissions from the latter are neither directly measurable nor determinable by the use of emission factors. Instead, aqueous cadmium emissions from non-point sources can only be assessed as mathematical residual of other data. Moreover, since this procedure involves the use of river-specific information (local cadmium load, characteristics of sedimentation process), it has to be carried out separately for each river under consideration.

Usually, the following basical relationship is employed in order to assess annual emissions from non-point sources:

$$(1) \quad L_2 = L_1 + (E_p + E_n) - S.$$

Here, L_1 and L_2 indicate the rivers cadmium load (tons/year) at two different monitoring stations numbered in downstream direction. E_p and E_n indicate point source and non-point source emissions which occur between the respective stations and S indicates the annual amount of cadmium which accumulate in the river-bed between the monitoring stations due to sedimentation processes. Hence, (1) states that the change in load between two monitoring stations equals the sum of point source and non-point source emissions minus the amount of pollutants which is accumulated by sedimentation. Rearranging gives:

$$(2) \quad E_n = (L_2 - L_1) - E_p + S.$$

According to (2) aqueous emissions from non-point sources can be assessed as residual of change in load, point source emissions and sedimentation. However, there is one problem which in most cases impedes the empirical employment of this relationship: Due to the high complexity of the respective physical and chemical processes adequate estimates of cadmium sedimentation in German rivers are not available. The only ex-

ception is the German part of the Rhine River for which usually is assumed that no sedimentation at all occurs¹⁰ (i.e. $S=0$). Hence, in this case there is no need to worry about sedimentation and aqueous emissions from non-point sources can easily be assessed as the residual from change in load and point source emissions.¹¹

However, even in the absence of sedimentation there remain (at least) two sources of error regarding the assessment of non-point emissions as residual from change in load and point source emissions: Firstly, it can not be excluded there may be unidentified emissions from unknown (perhaps illegal) point sources, and secondly the assessment of the cadmium load itself may be doubtful due to methodological shortcomings or monitoring problems (see below). Moreover, in the case of the Rhine River there is the problem that parts of it constitute the border between Germany and France, i.e. there are emissions from both countries which have to be distinguished.

Table 3.5 indicates the annual cadmium load (tons/year) of the major German rivers which discharge to the North Sea (Rhine River, Elbe River, Weser River and Ems River). The monitoring stations referred to in this table are selected in such a way as to show the change in cadmium load which occurs during the respective river passes through German territory. Therefore, table 3.5 contains the cadmium loads calculated for the first monitoring station after the river's entry to German territory and the last monitoring station before the river leaves German territory.¹²

¹⁰ However, as Elgersma et al. (1991, p.30) point out, this assumption may not be completely valid for each period of time and each part of the German Rhine River.

¹¹ This methodological advantage is the very reason why empirical studies on aqueous emissions from non-point sources in the FRG are generally limited to the Rhine River.

¹² In the case of the Elbe River the first station (Schnackenburg) is located at the border to the former GDR and the last station (Glückstadt) is located at the tidal limit. For the Ems River no first station is specified since this river springs on German territory.

Table 3.5: Cadmium load (tons/year) of major German rivers discharging to the North Sea.

<u>Rhine River:</u>			
	Load at first station (Weisweil)	Load at last station (Kleve-Bimmen)	Change in load
1982	6.3	50.5	44.2
1987	6.0	16.7	10.7
1989	3.2	9.5	6.3
<u>Elbe River</u>			
	Load at first station (Schnackenburg)	Load at last station (Glückstadt)	Change in load
1982	13.1	15.7	2.6
1987	16.0	11.5	- 4.5
1989	16.8	8.5	- 8.3
<u>Weser River</u>			
	Load at first station (Hemeln)	Load at last station (Intschede)	Change in load
1982	3.2	6.3	3.1
1987	2.5	3.2	0.7
1989	1.0	1.9	0.9
<u>Ems River</u>			
	Load at first station (- - -)	Load at last station (Herbrum)	Change in load
1982	0.0	0.8	0.8
1987	0.0	1.2	1.2
1989	0.0	0.5	0.5

Source: Own calculations; based on: Deutsche Kommission zur Reinhaltung des Rheins (1983, 1988, 1990), Arbeitsgemeinschaft für die Reinhaltung der Elbe (1983, 1988a, 1988b, 1990), Arbeitsgemeinschaft der Länder zur Reinhaltung der Weser (1983, 1988, 1990), Niedersächsisches Wasseruntersuchungsamt (1983) and Niedersächsisches Landesamt für Wasser und Abfall (1990).

The figures presented in table 3.5 strongly support the observation that annual cadmium emissions from industrial point sources have decreased enormously during the eighties. As a consequence, for all major rivers discharging to the North Sea the change in load between the first and the last monitoring station has declined considerably.^{13,14} However, this decline significantly falls short of the decline in point source emissions. In particular, the change in load of the Rhine River only decreased by a factor of appr. 5 between 1982 and 1989 whilst point source emissions decreased by a factor of more than 20 (see table 3.2). This difference supports the supposition that aqueous cadmium emissions from non-point sources have not decreased as much as emissions from point sources did. However, any attempt to assess the magnitude of non-point source emissions to the Rhine River from the load figures presented in table 3.5 seems to be doubtful due to two methodological problems:

- The usual way to calculate a river's cadmium load is to measure the cadmium concentration ($\mu\text{g Cd per litre}$) in its water and to multiply this figure by the throughput of water during the time period under consideration. In the case of the Rhine River cadmium concentration and throughput of water are measured at intervals of two weeks. For the German monitoring stations Weisweil and Kleve-Bimmen the respective figures are published by the German Commission for the Protection of the Rhine River (cf. Deutsche Kommission zur Reinhaltung des Rheins 1983, 1988, 1989, 1990). From these data the cadmium loads presented in table 3.5 are calculated by separately multiplying each concentration figure by the

¹³ The only exception is the Ems River where the cadmium load at the last station in 1987 considerably exceeds the load observed in 1982. This result, however, is due to measurement problems caused by a flood event in 1987.

¹⁴ The negative change in load obtained for the Elbe River indicates that total emissions fall short of the amount of cadmium which is accumulated in the river-bed due to sedimentation processes.

water throughput during the respective two week-intervall.¹⁵ However, due to the enormous decrease in emissions, which occurred during the eighties, the cadmium concentration at both monitoring stations under consideration began to drop below the employed verification limit of 0.3 µg/l for an increasing number of monitoring periods. In calculating the load figures of table 3.5 a concentration of 0.15 µg/l was assumed for each period below the verification limit. Due to this simplification, which is in accordance with the methodology applied by the German Commission for the Protection of the Rhine River, it has to be suspected that the calculated load figures do not fully reflect the real trend in cadmium emissions.

- The second problem is related to the already mentioned fact that a part of the Rhine River constitutes the border between Germany and France. Hence, there are emissions from both countries which have to be considered separately in calculating aqueous cadmium emissions from non-point sources. Such a differentiation, of course, is not possible on the sole base of the figures presented in table 3.5.

Both problems can, at least in part, be resolved by applying monitoring data from French and Dutch stations. These data are published by the International Commission for the Protection of the Rhine River (cf. Internationale Kommission zum Schutze des Rheins gegen Verunreinigungen 1989) which is the head organisation of the national commissions of France, Germany and the Netherlands.

The advantage of the concentration figures published by French and Dutch monitoring agencies comes from the fact that they are not subject to the restrained German verification limit of

¹⁵ To avoid confusion, it should be noted that this approach differs from the methodology used by the German Commission for the Protection of the Rhine River which merely multiplies the average annual cadmium concentration by the annual throughput of water. Therefore, the load figures published by the German Commission differ from the figures presented in table 3.5.

0.3 µg/l. The French and Dutch agencies report concentration data below 0.3 µg/l with an accuracy of two decimal digits. Of course, there are doubts about the accuracy of measurement of such small concentrations,¹⁶ but nevertheless, due to the lack of higher quality data it seems to be justified to employ these figures in order to assess aqueous non-point source emissions.

Table 3.6: Absolute cadmium load and change in load (t/year) of the Rhine River in 1988.

Monitoring station	Absolute Load (tons/year)	Change in Load (tons/year)
Village-Neuf	0.7	12.2
Seltz	12.9	6.7
Bimmen-Lobith	19.6	

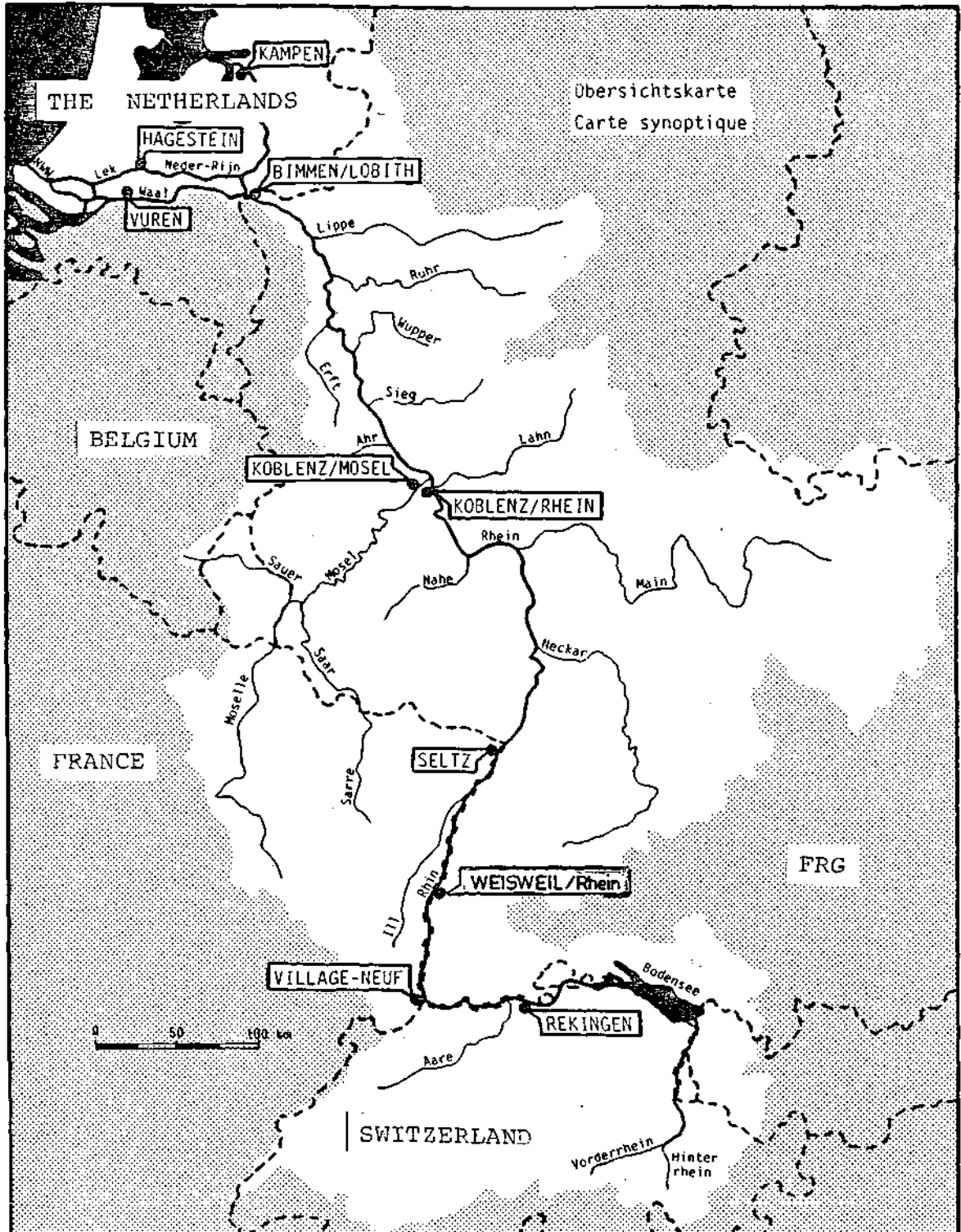
Source: Own calculations; based on: Internationale Kommission zum Schutze des Rheins gegen Verunreinigungen (1989).

Using the concentration and throughput data obtained at the monitoring stations Village-Neuf (France), Seltz (France) and Bimmen-Lobith (Germany/Netherlands)¹⁷ results in the load figures presented in table 3.6. Moreover, by the location of the monitoring stations under consideration the German part of the Rhine River can be subdivided into two segments which have to be treated separately (see figure 3.1): Along the first segment between Village-Neuf and Seltz the Rhine River constitutes the border between France and Germany, whereas along the

¹⁶ In particular it is known that even under ideal laboratory conditions the monitoring of concentrations in the range of 0.3 µg/l is already subject to variations of 20-30 %.

¹⁷ The concentrations at Bimmen-Lobith are averages of the figures obtained at the German monitoring station Kleve-Bimmen and the dutch monitoring station Lobith (see IKRR 1987, p.38).

Figure 3.1: Location of water quality monitoring stations at the Rhine River.



second segment between Seltz and Bimmen-Lobith the Rhine River passes exclusively through German territory. Hence, the change in load between Village-Neuf and Seltz is due to French as well as German sources whilst the change in load between Seltz and Bimmen-Lobith is solely due to German sources.

Since there are no significant industrial activities in the German part of the Rhine river basin between Village-Neuf and Seltz it seems to be reasonable to assume that the change in load between these two monitoring stations - 12.2 t/a - is solely due to 1) point source emissions from France, and 2) non-point source emissions from France and the FRG. According to Elgersma et al. (1991) annual French point source emissions in the Rhine River basin amounted to appr. 1.1 - 2.4 tons in 1988 (see table 3.2). This figure implies a difference between change in load and point source emissions of appr. 9.8 - 11.1 tons which may be interpreted as a rough guess of the approximate magnitude of non-point source emissions. Assuming that these emissions are equally distributed between France and Germany leads to the - even rougher - guess that there are appr. 4.9 - 5.6 tons of aqueous cadmium emissions from German non-point sources between Village-Neuf and Seltz.

Concerning the second segment of the Rhine River between Seltz and Bimmen-Lobith table 3.6 indicates a change in load of appr. 6.7 tons. Hence, accounting for annual point source emissions of appr. 2.9 tons in 1988 (see table 3.2) leads to appr. 3.8 tons of non-point source emissions between Seltz and Bimmen-Lobith.

From the calculations presented above it seems to be justifiable to assert that total non-point source emissions in the German part of the Rhine River basin amounted to a magnitude of appr. 8.7 - 9.4 tons in 1988. Accounting for point source emissions of about 2.9 tons (see table 3.2) this im-

plies a ratio between point source and non-point source emissions of at least 1:3.¹⁸

Assuming finally that the ratio between point source and non-point source emissions obtained for the Rhine River basin is representative for the FRG as a whole facilitates a projection of total non-point source emissions. Applying the ratio of 1:3 to the data presented in table 3.4 leads to a total of appr. 12.5 tons of aqueous cadmium emissions from non-point sources in 1988. It should be born in mind, however, that this guess is extremely speculative since it rests on several highly simplifying assumptions. Nevertheless, the message of these speculations is obvious: Aqueous cadmium emissions from non-point sources considerably exceed emissions from point sources.

Basically, there seem to be three major causes which are responsible for diffuse aqueous cadmium emissions in the FRG:

- 1) atmospheric deposition of cadmium to surface waters,
- 2) run off from sewage sludge disposal in agricultural use and
- 3) run off from the use of agrochemicals (cadmium containing phosphate fertiliser).

However, concerning the quantitative significance of these sources only sketchy information is available.

According to Böhm/Schäfers (1990, p.4) the annual atmospheric cadmium deposition over German territory amounts to approximately 1 kg/km² on the average. Accounting for an area covered by the German part of the Rhine River basin of appr. 102.000 km² (including tributaries) this deposition rate indicates that there may be an annual fall out of about 102 tons of cadmium over this area. This number clearly contradicts all estimates about airborne cadmium emissions in West Germany (see Section 4). The highest estimate of the Umweltbundesamt amounts to about 60 t/year for West Germany, i. e. at most

¹⁸ This result is in line with Stigliani (1990, p. 333) who asserts for 1985 that appr. 72% of cadmium emissions discharged to the Rhine River stemmed from diffuse sources.

half of the Böhm/Schäfers (1990) estimate. Although it may be possible that Böhm/Schäfers (1990) include airborne transfrontier transports of cadmium, we still have little confidence in their result. It seems more reasonable to use the magnitude of emissions of between 25 and 60 t/year in the early eighties. How much they contribute to diffuse water pollution is not clear since there is no information at all how much of this amount remains in the ground and how much leads to an increase in the Rhine River's cadmium load. It can, however, not be ignored that the atmospheric deposition contributes to aqueous cadmium emissions from non-point sources.

With respect to the disposal of sewage sludge to agricultural land, Böhm/Schäfers (1990, p. 21) claim that the cadmium input from this activity is subject to a rapidly declining. This trend is due to a considerable tightening of the legal restrictions concerning the agricultural use of sewage sludge in the FRG. Accounting for an application of appr. 600,000 tons per year with an average cadmium concentration of appr. 3.8 g/ton, a total annual cadmium load of about 2.3 tons (see Böhm/Schäfers 1990, p. 21)¹⁹ is contained in the sewage sludge on agricultural land. Hence, it seems to be reasonable to assume that sewage sludge disposal to agricultural used land does not significantly contribute to aqueous cadmium emissions from non-point sources.

Finally, the cadmium input caused by the application of phosphate fertilizer (P_2O_5) depends on the amount of fertilizer used and its cadmium concentration²⁰ which widely varies according to the country of origin. Table 3.7 summarizes the amount and the origin of phosphate fertilizers consumed in the FRG. Unfortunately, data concerning the average cadmium con-

¹⁹ In contrast to this figure, which is based upon monitoring data concerning the sewage sludge's cd-concentration, the authors of the ERL-Report (1989, p. 32) claim that the cadmium load due to the application of sewage sludge amounts to 19.7 tons.

²⁰ The cadmium contamination of phosphate fertilizer is caused by the natural cadmium content of the phosphate ore used in production.

centration are available only for domestic produced fertilizer but not for imports. According to Böhm/Schäfers (1990, p. 18) the average cadmium concentration of phosphate fertilizer from domestic production amounts to appr. 40 g/ton, whilst it is suspected that the concentration of imported fertilizer considerably exceeds this magnitude. Based on a total average of 75 g/ton Böhm/Schäfers (1990, p. 20) estimate an annual cadmium load of about 48.8 tons. However, to this figure the same problem as in the case of atmospheric depositions applies: It is not known how much of the fertilizers' cadmium load leads to water pollution due to run off processes.

Table 3.7: Consumption of phosphate fertilizer (P_2O_5) in the FRG (1000t).

	1980/81	1984/85	1985/86	1986/87	1987/88	1988/89
Domestic P_2O_5	510.0	393.6	329.5	272.4	234.0	245.2
Imported P_2O_5	197.1	283.0	358.0	363.2	408.7	353.4
Total consumption	707.1	676.6	687.5	635.6	642.7	598.6

Source: Böhm/Schäfers (1990).

Although there are considerable uncertainties about the amount and the sources of diffuse aqueous cadmium emissions two conclusions seem to be obvious from the discussion above:

- 1) There is strong evidence that aqueous cadmium emissions from non-point sources considerably exceed emissions from point sources. A reasonable ratio between point source and non-point source emissions seems to be appr. 1:3.
- 2) The main sources of diffuse aqueous cadmium emissions are atmospheric depositions and the run off from the use of agrochemicals. Although the relative contribution of these two sources can not be quantified, it is apparent that

measures aiming at reducing aqueous cadmium emissions from non-point source should primarily concentrate 1) on reducing emission to air and 2) on reducing the input of cadmium caused by the use of agrochemicals.

4. Airborne cadmium emissions

The distinction between point-source and diffuse emissions which has been introduced in Section 3 is only of minor relevance in the case of airborne emissions. The only known sources of diffuse cadmium emissions to the air are activities related to the storage, handling and transport of dust-spreading goods with high cadmium content like, e.g., zinc ore concentrate (see table 4.2). As Böhm/Schäfers (1990, p.4) note, there are no information available on the quantitative magnitude of these emissions.¹ However, in view of the figures to be discussed below, it seems reasonable to assume that airborne cadmium emissions from diffuse sources are quantitatively almost insignificant compared to the emissions from point sources.²

Table 4.1 summarizes the available information on airborne cadmium emissions by sectors in the FRG. However, the data sources compiled in this table are not as informative as it may seem at first glance. Except for the ERL-Report (1990) all estimates presented in table 4.1 are published in a rather sketchy way which does not facilitate a re-examination of the obtained results. In particular, information about the employed methodology and the underlying emission-coefficients is not provided. Hence, a cross-checking between the results of the different estimates is hardly possible and the quality of the data can not be judged. But, despite all differences the estimates presented in table 4.1 clearly indicate that there

¹ Note, that in contrast to the case of aqueous emissions it is not possible to calculate diffuse airborne emissions as residual of load figures and point source emissions.

² This view is also supported by the existence of strict legal regulations. According to the *Technical Directive on Air Pollution* ("Technische Anleitung zur Reinhaltung der Luft - TA-Luft") from 27.2.1986, emissions caused by storage, handling and transport of dust-spreading goods with a cadmium content of more than 50 ppm have to be minimized by employing the so-called 'most effective measures' ("wirksamste Maßnahmen"; see § 3.1.5.5 TA-Luft).

Table 4.1: Estimates of airborne cadmium emissions in the FRG by activities (tons/year).

Year under review:	1980/82	1982	1985/89	1985/86	1986
Data source:	BDI (1982)	UBA (1991)	ERL (1990)	BLAU (1988)	BLAU (1989)
Fossil fuel combustion by power plants and industrial furnaces					
- coal	2.2	1.4-5.6	6.4	1.3	2.3-3.3
- oil	0.5	0.2	3.9	0.1	0.2-1.0
Fossil fuel combustion by households and small consumers					
- coal	} 1.3	0.3	1.8	} 1.3	} 0.5
- oil	} .	< 0.01	1.0	} .	} .
Iron and Steel	5.0	2.2-14.3	6.0	< 3.0	4.85-12.1
Non-ferrous mining	.	.	0.05	.	.
Zinc refining	} .	14-24	8.4	} .	} .
Lead refining	} 5.0-7.0	1.2-1.8	0.9	} 2.4	} 12-20
Copper refining	} .	0.35-1.04	1.7	} .	} .
Battery manufact.	0.31	.	3.9	0.03	.
Alloy manufact.	0.5	.	0.18	1.4	.
Cement manufact.	0.3	0.09-0.36	1.1	< 0.2	0.2-1.4
Glass manufact.	3.0	0.25-1.00	.	.	1.1-2.6
Ceramic manufact.	.	4	.	.	0.3-0.6
Pigment manufact.	0.17	0.1-0.3	.	0.01	.
PVC manufact.	.	0.06	.	.	.
Incineration of household waste	2.9-3.8	1.1-5.3	7.2	< 2.0	3.3-6.0
Incineration of industrial waste	0.5-1.4
Incineration of sewage sludge	0.1	.	.	< 0.1	< 0.05
Motor traffic	.	0.6	1.75	.	.
Total	21.3-24.2	25.9-58.9	44.9	< 11.8	25.3-49.0

Source: Bundesverband der Deutschen Industrie (BDI, 1982), Bund-Länder-Ausschuß Umweltchemikalien (BLAU, 1988, 1989, ERL-Report (1990) and Umweltbundesamt (UBA, 1991).

there are basically five activities which are responsible for approximately 85-95% of total airborne cadmium emissions in the FRG:

- the combustion of fossil fuels (i.e. coal, oil) by power plants industrial furnaces and private households,
- the production of iron and steel,
- the production of non-ferrous metals (zinc, lead, and copper),
- the manufacturing of glass and ceramics, and
- the incineration of solid waste.

Airborne cadmium emissions caused by the other activities mentioned in table 4.1 (i.e. non-ferrous mining, motor traffic and manufacturing of batteries, alloy, cement, pigments and PVC) seem to be almost insignificant.

4.1 Combustion of fossil fuels

Hard coal, brown coal and oil contain a certain amount of cadmium (see table 4.2) which is partly released in form of cadmium contaminated flue dust during the process of combustion. The published figures of annual airborne cadmium emissions caused by power plants and industrial furnaces range from 1.3 tons to 6.4 tons resulting from the combustion of coal and from 0.1 tons to 3.9 tons resulting from the combustion of oil (see table 4.1). The wide span between the different estimates indicate that there is considerable uncertainty concerning the magnitude of emissions. However, in both cases the upper limits are claimed by the ERL-Report (1990) and it seems that these figures overestimate emissions.

This is particularly obvious in the case oil combustion: The emission coefficients employed in the ERL-Report (1990) are 0.25 gram of cadmium per ton of oil consumed by power plants and 0.145 gram of cadmium per ton of oil consumed by industrial furnaces. These coefficients can be checked against the cadmium content of fuel. Since oil-fired plants are usually

not equipped with dust filters (see Umweltbundesamt 1989, p.519) it may be possible that the emission coefficient is equal to the cadmium content, but it is not possible that the former figure exceeds the latter. However, according to estimates of the German Umweltbundesamt, published by Böhm/Schäfers (1990), the cadmium content of heavy oil ("Heizöl S") amounts only to 0.01 to 0.1 gram per ton (see table 4.2). Hence, the emission coefficients employed by the authors of the ERL-Report (1990) seem too high, and a re-calculation of their results using an average coefficient of 0.04 g cd/ton oil leads to an estimate of approximately 0.8 tons of airborne cadmium emissions caused by the combustion of oil in power plants and industrial furnaces. This magnitude is roughly in line with the figures published by the other studies (see table 4.1).

Table 4.2: Cadmium content (ppm) of fossile fuels and selected raw materials.

Fossil fuels:	
Hard coal	0.50 ppm - 10.00 ppm
Brown coal	0.01 ppm - 3.00 ppm
Heavy oil ("Heizöl S")	0.01 ppm - 0.10 ppm
Natural gas	negligible
Raw materials:	
Iron ore	0.12 ppm - 0.30 ppm
Dolomite, limestone	0.01 ppm - 0.70 ppm
Sand, clay	0.03 ppm - 3.00 ppm
Zinc ore concentr.	1000 ppm - 12,000 ppm
Lead ore concentr.	3 ppm - 500 ppm
Copper ore concentr.	30 ppm - 1,200 ppm

Source: Böhm/Schäfers (1990).

According to legal regulations concerning air pollution, coal-fired power plants and industrial furnaces in Germany are usually equipped with dust-filters. Since the amount of cadmium, that is released during the combustion process, condenses onto the fly ash particles, the respective cadmium emissions depend not only on the coal's cadmium content but also on the removal factor of the employed filter systems. While the cadmium content used in the ERL-Report (1990) is roughly in line with the estimates presented in table 4.2, there is a considerable inconsistency concerning the removal factor: The ERL-Report (1990) uniformly assumes for all ECE-member states that 9% of the coal's cadmium content is finally emitted to the air. In contrast to this, the removal factors of filter systems used by coal-fired plants in Germany usually amount to 98% and more (Böhm/Schäfers, 1990, p.9). Hence, it has to be suspected that cadmium emissions are lower than claimed in the ERL-Report (1990).

From the above discussion and from the figures presented in table 4.1 it seems reasonable to conclude that annual airborne cadmium emissions caused by power plants and industrial furnaces amounted to a magnitude of approximately 2 to 5 tons in the period of 1982 to 1986. This magnitude, however, can not be applied to the current situation since the legal background concerning air pollution by power plants and major industrial furnaces totally changed in June 1983 when the so-called *Ordinance on Large Combustion Facilities* ("Großfeuerungsanlagenverordnung") was introduced. According to this regulation new plants are required to meet very strict emission standards concerning SO₂, NO_x, suspended matter (dust) and other pollutants, and already existing plants have to be improved within specific transition periods. According to the Umweltbundesamt this regulation will lead to a 60% reduction in emissions of suspended matter from large combustion plants between 1983 and 1993 (see table 4.3). As a consequence, airborne cadmium emissions caused by these sources will also decrease considerably. This reduction, however, will probably be smaller than the

60%-reduction in suspended matter emissions mentioned above. This is due to the fact that cadmium, that is volatilized during combustion processes, preferably condenses onto fly ash particles smaller than 5 μm which can only partially be removed even by modern filter technologies (Ewers 1990, p.1).

Table 4.3: Annual emissions (1000 tons) of power plants and industrial furnaces regulated by the *Ordinance on Large Combustion Facilities* from 1983.

	1983	1988 ¹	1993 ¹
Sulphur Dioxide (SO ₂)	1,940	700	400
Nitrous Oxides (NO _x)	960	590	250
Suspended Matter	100	60	40
¹ estimates			

Source: Umweltbundesamt (1989, p. 519).

In the case of fossil fuel combustion by households and small-scale consumers the large differences between the estimates of the ERL-Report (1990) and the other studies can not be explained by means of the published data and material. However, accounting for the growing diffusion of district-heating-systems ("Fernwärme") and in view of ongoing substitution processes in favour of cadmium-free natural gas (see Umweltbundesamt 1989, pp. 559-560), it may be concluded that the amount of airborne cadmium emissions from the combustion of fossil fuels by households and small-scale consumers will in any case become negligible in the medium-term.³

³ This trend will also be supported by the so-called *Ordinance on Small Combustion Facilities* ("Kleinfeuerungsanlagenverordnung") enacted in July 1988. According to this regulation coal-fired small-scale facilities with a nominal heat capacity ("Nennwärmeleistung") of more than 15 kilo-watt and oil-fired small-scale facilities with a nominal heat capacity of more than 28 kilo-watt have to meet certain emission standards concerning suspended matter.

4.2 Production of iron and steel

Cadmium enters the process of iron and steel making in two ways: as an undesired trace element of natural iron ore (see table 4.2) and as a contamination of scrap metals which results from the intentional employment of cadmium in surface plating. According to Böhm/Schäfers (1990, p.7) the cadmium input caused by the use of natural iron ore is negligible compared to the huge amounts of cadmium which enter the process via scrap metals. However, the scrap metals cadmium content varies widely and therefore suitable coefficients describing airborne cadmium emissions from iron and steel making can hardly be determined. This problem leads to considerable uncertainty concerning the actual magnitude of emissions. In particular, the estimates of the Umweltbundesamt (1991) exhibit an extremely wide span of uncertainty which ranges from a lower bound of 2.2 tons per year to an upper bound of 14.3 tons per year (see table 4.1). However, the Umweltbundesamt (1991) additionally provides a mean value of 6.9 tons which is roughly in line with the other estimates shown in table 4.1.

The data discussed above suggest that a magnitude of 5 - 7 tons may be viewed as a rough guess of annual airborne cadmium emissions from iron and steel making in the period of 1982 to 1986. However, as will be shown below, there are two reasons to believe that this magnitude can not be applied to the current emissions from iron and steel making.

The first reason is related to a change in the legal requirements concerning air pollution by iron and steel making which are laid down in the so-called *Technical Directive on Air Pollution* ("Technische Anleitung zur Reinhaltung der Luft - TA-Luft"). This regulation, originally introduced in 1974, has been tightened considerably in 1986 (see table 4.4). In particular, the emission standard concerning the permissible amount of suspended matter per m^3 of exhaust air caused by the electric arc process have been reduced from 150 mg to 20 mg.

This requirement is of particular importance with respect to airborne cadmium emissions because scrap metals are usually recycled by means of the electric arc method (see Elgersma et al. 1991, p. 77). Hence, it has to be expected that the tightened emission standards, which have to be met by each plant

Table 4.4: Change in regulations of the *Technical Directive on Air Pollution ('TA-Luft')* that are important with respect to airborne cadmium emissions.

<u>Permissible Concentration of suspended matter in exhaust air of regulated sources</u>		
	TA-Luft 1974	TA-Luft 1986
General standard	150-500 mg/m ³	50-150 mg/m ³
Special standards:		
- Iron and steel production		
* Electric arc process	150 mg/m ³	20 mg/m ³
* Basic oxygen process	no special standard	20-50 mg/m ³
- Lead refining	20 mg/m ³	10 mg/m ³
- Zinc and copper refining	no special standard	20 mg/m ³
<u>Permissible Concentration of heavy metals in exhaust air of 'high-polluting' sources</u>		
	TA-Luft 1974	TA-Luft 1986
Scope of application:	Sources that emit more than 0.5 kg/h of heavy metals	Sources that emit more than 1 g/h of Cd, Hg and Thallium
Emission standard:	Total concentration of heavy metals in exhaust air is not allowed to exceed 20 mg/m ³	Total concentration of Cd, Hg and Thallium in exhaust air is not allowed to exceed 0.2 mg/m ³

until 1996, will lead to a significant reduction in airborne cadmium emissions compared to the period of 1982 - 1986.

The second reason is related to the observation that the cadmium content of scrap metals can mainly be traced back to the use of cadmium in plating activities. According to Böhm/Schäfers (1990, p.8) the average lifetime of plated metal parts ranges from 15 to 25 years. Hence, it seems reasonable to assume that the cadmium input to the production of iron and steel is mainly determined by the amount of cadmium used in plating with an average time lag of approximately 20 years. As can be seen from table 2.2, the amount of cadmium employed in these activities is subject to an ongoing process of decrease since 1976.⁴ This implies that the cadmium input through scrap metal probably will begin to decline in the mid-nineties. The figures presented in table 1.* suggest that this process will lead to a decrease of cadmium input by a factor of more than 3 within the next 15 years. This time-lag effect, accompanied by the tightened emission standards discussed above, will induce a drastic reduction in airborne cadmium emissions caused by iron and steel making.

4.3 Production of non-ferrous metals

Raw zinc ores, lead ores and copper ores contain a certain amount of cadmium contamination (see table 4.2) that is partly volatilized and released to the exhaust air during the process of refining. According to the particularly high cadmium content of zinc ores - the respective estimates range from 1 g Cd/ton to 12 g Cd/ton (see table 4.2) - zinc refining has to be viewed as one of the most important sources of airborne

⁴ This decrease is in part due to substitution processes in the automobile industry. According to the *Advisory Board on Environmental Issues* (Rat von Sachverständigen für Umweltfragen, 1990, p. 230) one of the major German producers succeeded in reducing the cadmium content per motor car from 500 grams to 1 gram.

cadmium emissions (see table 4.1). The specific amount of cadmium emitted to the air strongly depends on the type of refining process that is applied. Significant differences in airborne cadmium emissions exist between the high-polluting thermal process ('Imperial Smelting') and the low-polluting electrolytic process. According to the ERL-Report (1990) the emission coefficient of thermal zinc refining as operated in the FRG amounts to 58 gram of Cd per ton of zinc produced, whilst the respective coefficient for the electrolytic process is only 0.2 g Cd/t. As a consequence, the major part of airborne cadmium emissions caused by zinc refining can be traced back to the use of the thermal process. With respect to the FRG it is estimated that in 1985 the thermal processes' share on total airborne cadmium emissions caused by zinc refining amounted to more than 99.4% (see ERL-Report 1990). However, since the mid-eighties the thermal process has been considerably reduced in capacity and it probably will be faced out in the FRG by now. Hence, the emission data presented in table 4.1 can not be applied to the current situation. In view of the technological development discussed above it seems justified to claim that the remaining airborne cadmium emission from primary zinc refining in the FRG may be almost negligible by now.

Concerning primary production of lead and copper the published material does not allow to check if the emission data presented in table 4.1 are still valid. However, since primary zinc and lead winning are sometimes linked within the same plant (see Elgersma et al. 1991, p.38) it may be reasonable to assume that the current emissions caused by primary lead production also will be smaller than indicated by table 4.1.

The secondary production of non-ferrous metals by utilizing scrap materials constitutes a further significant source of airborne cadmium emissions. As can be seen from the production data presented in table 4.5 secondary production is of particular importance in the cases of lead and copper winning. With

respect to the FRG it is estimated that in 1985 secondary production of lead contributed for 66% of total airborne cadmium emissions caused by lead winning, and the respective share concerning copper amounts to 50% (see ERL-Report 1990). However, due to a lack of more recent data it can not be judged if these figures still can be applied to the current situation.

Table 4.5: Primary and secondary production of non-ferrous metals (1000 tons) in the FRG 1982 - 1988.

	1980	1982	1984	1986	1988
Zinc:					
Primary production	365.2	333.6	356.3	370.9	352.4
Secondary production	27.8	31.5	30.8	26.6	42.5
Lead:					
Primary production	191.1	201.6	191.9	182.1	176.6
Secondary production	159.2	148.9	165.3	184.5	168.5
Copper:					
Primary production	153.9	161.8	148.8	161.9	162.5
Secondary production	219.9	231.8	230.0	260.0	263.9

Source: Metallgesellschaft (1989).

Finally, it should be noted that both primary and secondary production processes have recently become subject to considerably tightened regulations which are laid down in the amended version of the *Technical Directive on Air Pollution* from 1986 (see table 4.4):

1. The standards concerning the general emission of suspended matter from non-ferrous metal industries have been reduced to 10 mg/m³ for lead refining and 20 mg/m³ for zinc and copper refining respectively, and

2. the permissible total concentration of cadmium, mercury and thalium in exhaust air of 'high polluting' sources has been reduced to 0.2 mg/m^3 .

According to the *Advisory Board on Environmental Issues* (Rat von Sachverständigen für Umweltfragen, 1990, p. 231) this strenghtening of regulations will - at least in the case of high-polluting sources - induce considerable reductions in cadmium emissions. The total decrease in cadmium emissions is expected to reach the order of 30-40%.

4.4 Manufacturing of glass and ceramics

Cadmium enters the process of glass and ceramic manufacturing on two ways: as undesired trace element of raw materials like clay, sand, limestone and dolomite (see table 4.2) and as ingredients of pigments used for colouring. According to Böhm/Schäfers (1990, pp.8-9) the first route of cadmium input dominates in the manufacturing of heavy ceramics (e.g. bricks, potteries) and commodity glasses (e.g. plate glass) and the second route dominates in the manufacturing of fine ceramics (e.g. sanitary) and special glasses (e.g. for traffic lights).

According to the studies compiled in table 4.1 airborne cadmium emissions from the manufacturing of glass and ceramics amount to approximatively 1.4 - 5.0 tons per year. It may be speculated that the major part of this amount can be traced back to the use of cadmium containing pigments. Although this view can not definitively be substantiated by means of the published figures and materials it seems to be strongly supported by the fact that the colouring process operates at extremely high temperature levels that induce major parts of the cadmium input to evaporate into the exhaust air. Assuming that 5/6 of the cadmium input are votalized and released to

the exhaust air,⁵ accounting for 35 tons of cadmium used in the colouring of glass and ceramics (see table 4.6) and assuming that the removal factor of the employed filter systems amounts to 90 - 95% leads to an estimate of approximately 1.45 - 2.9 tons of airborne cadmium emissions caused in 1987 by the use of cadmium containing pigments in the colouring of glass and ceramics. This result is roughly in line with the figures presented in table 4.1.

Table 4.6: Destination of cadmium used in pigments.

	1983		1987	
	tons	%	tons	%
Plastics	250	82.2	250	85.9
Paints	20	6.6	6	2.1
Ceramics	23	7.6	24	8.2
Glass	11	3.6	11	3.8
Total	304	100.0	291	100.0

Source: Böhm/Tötsch (1989, p. 48).

In order to provide an idea of the current development of airborne cadmium emissions caused by the manufacturing of glass and ceramics it should finally be noted that these activities also are subject to the tightened regulations of the *Technical Directive on Air Pollution* already mentioned in the preceding sections. Concerning the activities under consideration especially the reduction of permissible heavy metal concentration in the exhaust air of 'high-polluting sources' (see table 4.4) seems to be suited to induce a significant decrease in airborne cadmium emissions. Hence, it may be suspected that the

⁵ This fraction is claimed by Böhm/Tötsch (1989, p. 84) for the colouring of glass. We assume that it can also be applied to the colouring of ceramics.

current emissions caused by the manufacturing of glass and ceramics are smaller than indicated by the figures presented in table 4.1. Further quantifications, however, are not possible due to a lack of more recent data.

4.5 Incineration of solid waste

Beside the production of iron and steel from scrap metals the incineration of waste is a second case in which the intentional use of cadmium in upstream activities leads to the inadvertent entry of cadmium into downstream activities. The amount of airborne cadmium emissions caused by the incineration of waste depends on two quantities:

1. the cadmium contamination of waste, caused by cadmium containing waste products (plastics, batteries etc.), and
2. the removal factor of the filter technologies employed (measured as the percentage of cadmium input that is not emitted to the air).

Suitable coefficients concerning the cadmium content of waste are available only for household waste but not for industrial waste. This lack of data, however, seems to be of minor importance since the major part of airborne cadmium emissions from waste incineration can be traced back to household waste (see table 4.1).

Table 4.7 summarizes the available data on the cadmium content of household waste and the efficiency of filter technologies used in waste incineration. As can be seen from this table there is considerably uncertainty with respect to both quantities. As a result, the respective emission figures presented in table 4.1 vary widely. In particular, the estimates of the Umweltbundesamt (1991) exhibit a considerable span of uncertainty that ranges from 1.1 to 5.3 tons per year. Additionally, the Umweltbundesamt (1991) provides a mean value of 2.5 tons. This figure seems to be reasonable accounting for the

Table 4.7: Cadmium content of household waste, removal factor of filter technologies, and calculated emission factors of waste incineration

	cadmium content (g Cd/t waste)	removal factor (%)	emission factor (g Cd/t waste)
ERL-Report (1990)	9.8	88.4	1.1
Böhm/Schäfers (1990)	10.0	92.5 - 95.9	0.4 - 0.8
RfU (1991)	3.5 - 8.7	.	.
Reimann (1991)	3.0 - 15.0	.	.

Source: ERL-Report (1990), Böhm/Schäfers (1990), Rat von Sachverständigen für Umweltfragen (1991), Reimann (1991).

coefficients shown in table 4.7 and the quantities of waste burned shown in table 4.8.

It has to be assumed, however, that the quantities discussed above are not suitable to describe the current and the future development concerning airborne cadmium emissions from waste incineration. This is due to the fact that the incineration of waste recently has become subject of dramatically tightened le-

Table 4.8: Incineration of municipal and industrial waste (1000 tons) in the FRG 1980 - 1987.

	1980	1982	1984	1987
Municipal waste	6,253	6,340	7,185	7,962
Industrial waste ¹	4,111	4,080	4,637	4,892
Total	10,364	10,420	11,822	12,854

¹ includes mainly household waste
² including industrial waste treated by municipal incineration plants

Source: Statistisches Bundesamt (1984, 1987, 1990b, 1991).

Table 4.9: Expected development of emission coefficients of waste incineration according to the amended *Technical Directive on Air Pollution* (1986), the *Ordinance on Waste Incineration Plants* (1990) and the expected technological progress until 1996.

	1986	1990	1996
g Cd/t waste	0.92	0.23	< 0.05
mg Cd/m ³ exhaust air	0.20	0.05	< 0.01

Source: Reimann (1991).

gal regulations. Not only the strict standards concerning the emission of heavy metals by 'high polluting sources', laid down in the amended version of the *Technical Directive on Air Pollution* of 1986 (see table 4.4), apply to waste incineration but also the newly introduced *Ordinance on Waste Incineration Plants* ('Verordnung über Verbrennungsanlagen für Abfälle') of 1990. According to the latter regulation an emission standard of 0.05 mg cd/m³ exhaust air has to be met by each incineration plant until 1996. As calculated by Reimann (1991) this requirement standard implies an average emission coefficient of 0.23 g Cd/ton waste. This means an improvement by a factor of four compared to the requirements of the *Technical Directive on Air Pollution* of 1986 (see table 4.9). Moreover, the future state of the art is expected to bring about an emission coefficient of 0.05 g Cd/ton waste (see table 4.9). Hence, it may suspected that technical progress will lead to drastic reductions in airborne cadmium emissions from waste incineration. However, this trend may partly be compensated by an increasing amount of waste treated in incineration plants. According to Böhm/Schäfers (1990) the capacity of municipal incineration plants will increase by roughly 8 million t/a within the next few years. Therefore, it may be expected that waste incineration will continue to be one of the major sources of airborne cadmium emissions.

5. Conclusions

Cadmium is the most toxic heavy metal, hence it requires considerable attention even in situations where it appears in low concentrations. Its ability to accumulate over a long time horizon in human bodies makes it a potential threat for especially older people. The danger of cadmium for human beings contrasts significantly with the little knowledge about the cadmium flows in the environment and - more specifically - in the economy. In this paper all available information about the sources and the fate of cadmium have been selected and evaluated.

In this final chapter we take the freedom to leave the realm of discussing the different estimates of cadmium flows and enter the arena of speculation. Since the existing estimates often go back to the early 1980's and use data about outdated technologies for the extrapolation of emissions, guesses about today's emissions and likely future emissions given today's regulatory framework require a courageous amount of judgement. The following conclusions should therefore be read with this caveat in mind.

5.1 Cadmium Flows

The account of cadmium flows is complicated by the different paths in which it moves between different environmental media. Whereas over 1,000 tons of cadmium are added to the stock of cadmium in the human environment in West Germany every year, the total flow through the economy is about 3,000 tons. The additional 1,000 plus tons become incorporated into products with very different life-times. These products then are disposed of or become recycled thus reentering production processes. Their contribution must be important if one considers that the flow is almost three times higher than the change in

stock. This also means that the intentional use of cadmium in production is less important than the unintentional input through contaminated materials. Measures to reduce the flow of cadmium therefore depend to a considerable extent on past decisions about the use of cadmium in products.

The intentional use of cadmium is relatively well documented such that the cadmium content of these products is known. The content of products and emissions of processes in which cadmium enters as a contamination is practically unknown. These contaminations come from recycled materials as well as from raw materials containing cadmium as a trace element. Hence, even if the intentional use of cadmium were to be reduced, the inadvertent input would still need to become controlled. Ironically, a waste management based on increased collection and sorting would also channel cadmium back into production processes and would thus increase cadmium flows.

Cadmium which is not contained in products will be returned to the environment, i.e. air, water and soils. In this paper the estimates on air and water emissions are reported. We have not shown any data on depositions on the ground since this is completely unknown. Also little is known about the fate of cadmium once it has entered air and water: Since a maximum of about 100 tons of cadmium per year has been emitted in the air and into the water in the 1980's the direct deposition into waste disposal facilities must be quite large.

Future cadmium flows are hard to predict because these different factors influence the input of cadmium in the human environment. The development of the 1970's and 1980's could be characterized as a period with slight reductions in the intentional use of cadmium paired with strong reductions of emissions into air and water although the unintentional use has most likely increased due to the rising industrial activity overall.

5.2 Emissions: Past, Present and Future

Most studies on cadmium emissions into the air rely on primary data sources from the early 1980's. The results of these studies are shown in Table 4.1 which reveals that somewhere between 25 and at most 60 tons of cadmium have been emitted in that time period with the most important contributors being

- the iron & steel industry through scrap melting
- the combustion of fossil fuels, mostly coal,
- the manufacturing of ceramics, and
- the incineration of household waste.

Since then, the regulations concerning emissions of flue dust which carries airborne cadmium emissions have been considerably tightened by the "TA-Luft", the "Großfeuerungsanlagenverordnung", the "Kleinfeuerungsanlagenverordnung" and the "Verordnung über Verbrennungsanlagen für Abfälle". The industry has reacted to the new emission standards by applying better end-of-pipe technologies and by introducing production processes which have lower emission factors. The current time is a transition period during which the dissemination of the new techniques takes place. Our guesses about the result of this diffusion are summarized in Figure 5.1 which is based on the UBA-estimates for 1982 (see table 4.1).

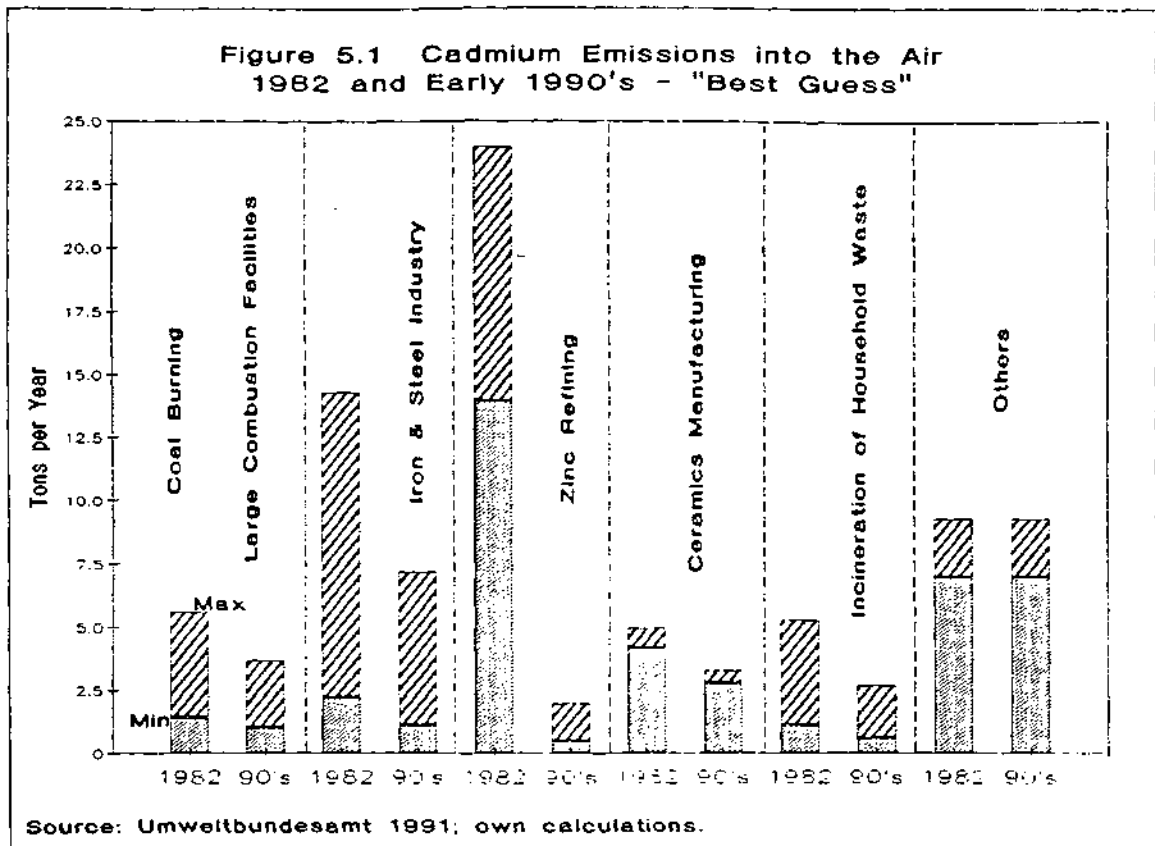
We have made the following assumptions for the five major emitters of cadmium:

- The regulations on the combustion of fossil fuels have induced the installation of better end-of-pipe technologies which have led to a 30% reduction of cadmium emissions from burning fossil fuels.
- The iron & steel industry is increasingly using electric arc processes with lower emission coefficients and is subject to much tighter emission standards (table 4.4) such that a 50% reduction between 1982 and today seems reasonable.

- The emissions through the joint production of zinc and cadmium depend predominantly on the process technology. For imperial smelting emission factors are reported which are hundred times higher than those for the electrolytic process. Since in Germany thermal processes are practically faced out, we assume that between 0.5 and 2 tons of cadmium are still emitted.
- In the glass and ceramics industry only improvements of end-of-pipe technologies are available. Since these industries are also regulated by the "TA-Luft" we also assume a 30% reduction in cadmium emissions since 1982.
- The strongest reduction in permitted emissions has taken place for waste incineration. We therefore assume a 50% reduction in cadmium emissions.

Taken these reductions together and assuming that the other sources of emission did remain constant we guess that the emissions in 1982 - as estimated by the UBA - amounting to between 25.9 and 58.9 tons have been reduced to about 13 to 23.6 tons in the early 1990's. Figure 5.1 shows that the most important contribution came from the technology switch in the zinc industry.

The medium-and long-run development of air born cadmium emissions depends on a number of sector-specific factors. Emissions of coal burning power plants would be strongly reduced if the requirement of the "Jahrhundertvertrag" which forces the power industry to burn domestic coal instead of gas or oil would be reduced. In addition, further improvements in filter technologies could lead to some additional reductions. This is also true for the glass and ceramics industry. The emission standards for industrial thermal processes are not yet as tight as those for waste incineration. These additional reductions must probably be paid with strongly rising marginal costs. Some of the tighter standards have already been incorporated for the period after 1996 in the current directives.



The emissions of the iron & steel industry will be reduced significantly after the middle of the 1990's. This is due to the input of scrap metal which enters production processes with a time lag of about 20 years after production. Since the peak of cadmium consumption in metal plating was in 1976, the cadmium content of scrap metal will possibly increase until the mid 1990's and fall thereafter.

The emissions of cadmium into rivers and lakes can be grouped on the one hand as coming from point and non-point sources, and on the other hand, as resulting from intentional and unintentional use of cadmium in economic processes. Whereas point sources are comparatively easy to estimate, non-point sources by their very nature are almost impossible to measure. Non-point sources therefore can only be assessed by comparing cad-

mium loads in rivers with the emissions of point sources. The difference then can be attributed to diffuse emissions, but only if the sedimentation of cadmium does not provide another complication which has to be accounted for. For this reason, we have only used data of the cadmium load in the Rhine river basin, since in the Weser, the Ems and the Elbe loads can hardly be measured accurately due to complex conditions in the tidal zones of these rivers.

In Figure 5.2 we have collected the most plausible magnitudes of aqueous emissions in West Germany. The three numbers refer to the late 70's, to 1983/84 and to 1988. Since the difference between cadmium emissions from point sources and cadmium loads was about equal in 1982 and 1988 we assume - given the lack of better information - that non-point emissions remained constant over this period. Figure 5.2 shows that the emissions of point sources have been drastically reduced such that non-point sources which were only one sixth of point sources at the end of the 1970's are now about three times higher than point sources. The potential for reducing emissions of point sources, therefore, seems to be almost exhausted by today. Hence further reductions in the cadmium load of rivers need to be achieved through measures which reduce non-point emissions.

Figure 5.2: "Best Guess": Aqueous Cadmium Emissions from Different Sources in West Germany
1978-82 / 1983-84 / 1988

	Point Sources	Non-point Sources
Intentional Use	9 / 4 / 0.5	0
Inadvertent Use	61 / 29 / 3.6	≈ 12
Sum	70 / 33 / 4.1	≈ 12

Source: Own calculations; based on tables 3.2, 3.4, 3.5, 3.6.

The major sources of non-point emissions into rivers come from the deposition of airborne cadmium emissions and from the use of phosphate fertilizers. Although it is known how much cadmium is emitted into the air - in the early 1990's probably between 13 and 23 tons per year - and applied through phosphates - around 50 tons per year -, we do not possess information about the diffusion of these loads. Some of the airborne emissions are "exported" through atmospheric transports, other emissions are "imported", then they are deposited in the soil. Together with cadmium in phosphates, these depositions can enter the biomass since plants accumulate cadmium quite easily, they can stay in the ground, or they can be washed out into rivers and lakes.

Attempts to further reduce cadmium loads in rivers need to address these diffuse sources. A reduction in the cadmium content of phosphates and a reduction of phosphate uses in agriculture could limit the cadmium input into the soil. By how much and in which time horizon this may become noticeable in reduced cadmium loads of rivers remains open, however. Further research is needed in order to understand how heavy metals accumulate in the soil and how they become transported into waterways. Similar problems arise with the deposition of airborne cadmium emissions.

5.3 Potentials for Reducing Cadmium Emissions

The data which have been analysed in this paper reveal that the remaining potentials for reducing cadmium emissions have changed considerably over the last ten years. The regulations with respect to emissions into water and air have led to a remarkable reduction of cadmium in these two environmental media: between around 1980 and today of up to 50% in air emissions and for emission into rivers the reduction may be as high as 70% to 80%. Naturally, once the easy options are exhausted further reductions may be more difficult from a

technological perspective and more costly from an economic perspective.

It is beyond the scope of this paper to give a detailed account of further potentials for reductions. The findings in this paper, however, point out specific directions in which progress seems possible, likely, and cost efficient. Further research will be needed to assess these proposals in detail. Figure 5.3 describes different strategies for reducing cadmium emissions into the two media, water and air. The first strategy for reducing emissions consists of using less cadmium in the first place, hence cadmium substitution is one important option. The second is concerned with those production processes in which cadmium is indispensable, but where process changes can significantly reduce emissions. The final option is the use of end-of-pipe technologies for separating out cadmium from other emissions.

Figure 5.3: Potentials for Reducing Cadmium Emissions

	Cadmium Substitution	Process Changes	End-of-Pipe Measures
Emissions into			
• Air	XX	O	X
• Rivers	XX	X	O
O: little potential for further reductions X: potential for further reductions XX: large potential which is beginning to become implemented			

The substitution of cadmium by other substances is gaining increasing importance. Böhm/Tötsch (1989) report that there are still potentials for substituting cadmium. According to their assessment, excessive product quality standards often

limit the substitution with other substances. It should be noted, however, that - although such substitution reduces the cadmium input and also cadmium emissions - the substitutes may also be harmful to the environment.¹ The substitution will predominantly reduce the increase in the stock of cadmium and its eventual deposition on the ground, whereas due to the already low emission factors into water and air these emissions will be influenced to a smaller extent.

As far as process changes are concerned there is little potential for further reductions of airborne emissions since - at least in Germany - these point sources have to a large extent already introduced low-emission processes. The major contributor for aqueous emissions from production processes is the use of phosphates in agriculture. This input of cadmium could significantly be reduced through a reduction of fertilizer use and through the use of phosphates with low cadmium content. In addition, technologies for extracting cadmium from phosphates are being developed.

End-of-pipe technologies from emissions into the water can hardly become improved. The extremely low emissions into rivers reveal that up-to-date end-of-pipe technologies have been introduced. The situation is somewhat different for cadmium emissions in the flue gas where different standards regulate different sources. The most stringent standard applies to waste incineration, but it is not clear why such a standard could not be imposed upon other combustion processes as well. It should be mentioned, however, that the costs of meeting such standards are high thus raising the question whether the same sum invested in other reduction activities could yield a better result than in end-of-pipe technologies for airborne emissions.

¹ An example is the use of cadmium stabilizers in plastics which could be replaced by lead stabilizers. In order to achieve the same results five times more lead than cadmium is required. Incidentally, the toxicity of cadmium is also considered to be five times higher than that of lead.

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