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RADIOACTIVE POLLUTANTS

Impact on the environment

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EDP SCIENCES

INSTITUT DE PROTECTION ET DE SURETE NUCLEAIRE

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(Based on invited papers at the ECORAD 2001 International Conference)

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Preface

Since the early forties, radioecology has, often in an emergency situation, been faced with the need to evaluate the impact that the military or civil use of nuclear energy has had on the environment. Radioecology developed in parallel with other ecological disciplines especially ecotoxicology, in part through the use of tracers. Radioecologists have aimed to understand processes controlling the environmental transfer of radionuclides and to integrate them into predictive models as well as engineering and restoration techniques. Experience of providing radioecological methods to mitigate the effects of accidents has emphasized the importance of the concept of sustainable development. It has also contributed to the recognition of a second key concept, the precautionary principle, and its practical application in the environment.

On the threshold of the 21st century, radioecologists have needed to take stock of the situation and to widen their perspectives. In response to this need, IPSN decided to gather a worldwide assembly by organizing the ECORAD 2001 Conference. This book collates a series of invited contributions at this conference which reflect on on-going discussions and provide reviews of the most up-to-date scientific and technical information regarding continental and estuarine environments. Within this context, and further to defining the current state of the art, the papers also identify possible research themes for the future along with scientific and ethical issues which are becoming increasingly important in response to public concern with respect to environmental radioprotection.

Continuing previous similar publication achievements, which particularly focused on the marine environment, IPSN has decided quite naturally to edit this document within its Book series dedicated to radiological protection and nuclear safety. This complements a former publication dedicated to *Radionuclides in the Oceans*, (P. Guéguéniat, P. Germain and H. Métivier, Eds., EDP Sciences, Les Ulis, 1996). The focus here is now on continental and estuarine environments which are addressed through four major chapters. Part 1 addresses the general environmental issues, encompassing radioactivity measuring methods, toxicants impact on the environment either in chronicle or accidental situations, and environmental radioprotection. Parts 2 and 3 refer to the state of the art in terrestrial and freshwater aquatic environments, respectively, and part 4 concludes by addressing the important societal and ethical issues.

It is of importance to recall that the production of this book, achieved within a very tight schedule, has been made possible by the very deep and scrupulous involvement of a number of international experts and professionals, within and outside IPSN, who enthusiastically dedicated their time to the number of tasks requested. They all deserve our gratitude, with especial acknowledgements to authors, and also to reviewers: Jean Aupiais, Rodolfo Avila, Jean-Claude Barescut, Nick Beresford, Dominique Boust, Philippe Calmon, Jacqueline Garnier-Laplace, Tom Hinton, Christian Hurtgen, Valery Kashparov, René Kirchmann, Henri Métivier, Valérie Moulin, Jean-Marc Peres, Gennady Polikarpov, Claire Sahut, Pascal Santucci, Jim Smith, Hervé Thébault, Pierre Toulhoat, Christian Vandecasteele, Gabriele Voigt, Dennis Woodhead. The readers should bear in mind that this book only forms the starter of the ECORAD 2001 conference meal. The remaining scientific matter which has been selected as high quality and relevant by the Scientific Committee will be further published as Proceedings of the conference in the Radioprotection Colloquium series as we did in 1997 with part 1 of the RADOC conference (*Radionuclides in the Oceans* –RADOC 96–97, Proceedings Part 1, Inventories, Behaviour and Processes, Octeville, 7-11 October 1996, *Radioprotection–colloques*, **32**, C2, April 1997).

Finally, it is with a great pleasure that we want to warmly thank all involved scientists and experts themselves, from students to leaders. They are those who dedicate their time, and often their life, to continuously improving the understanding of our common world to the benefit of humankind.

August 2001, The Editors

F. Bréchignac and B.J. Howard

Summary

Part 2
Radionuclides in terrestrial environments

Part 3
Radionuclides in aquatic environments

Part 4
Ethical and environmental issues

Foreword: Thoughts on Radioecology by the millennium shift

A. Aarkrog [1]

Radioecology has throughout the last half of the twentieth century developed into a science, not only dealing with nuclear contamination, but also contributing to our understanding of general environmental pollution problems. The major milestones during the past fifty years were the studies of global fallout, the waterborne discharges from nuclear reprocessing and the Chernobyl accident. These events have given us a good understanding of the environmental behaviour of major radio-contaminants such as ^{90}Sr, ^{131}I, ^{137}Cs and Pu. The present trends for radioecology involves a further development of models, tracer studies, countermeasures, and inclusion of other species than man in radiological protection. A major task will be a continued effort to inform and educate both the general public, including politicians and news media, but also scientists from developing countries. It would also be desirable to see radioecology closer integrated into environmental studies of other pollutants for instance by developing equidosimetric methods and studying possible synergistic and antagonistic effects. Finally an effort should be made to develop radioecology into a more hypothesis-oriented science. In a millennium perspective, we may envisage an impact from the rapidly evolving bio- and computer technologies and we may even see radioecology as an extraterrestrial science.

Introduction

The word Radioecology may be translated as housekeeping with radioactive substances. I define radioecology as the scientific discipline, which studies the environmental behaviour of radionuclides comprising their interaction with the bio- geo- atmo- and hydrospheres. The primary

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purpose of radioecological studies have been – and are still to a large extent – to provide dose assessments for environmentally dispersed radionuclides.

The science of radioecology was developed almost simultaneously in the Former Soviet Union (FSU) and in the United States (USA). This occurred by the entrance to the "Nuclear Age" in the late forties and early fifties.

The Russian geneticist Timofeev-Ressovsky (1957) organised a radiation biology laboratory near Sverdlovsk (now Ekaterinburg) in the southern Urals. He used the term "radiation biogeocenologie" for his studies of the behaviour of the radionuclides released to the environment in connection with the development of the first Soviet nuclear weapon at "Chelyabinsk-60" (later MAYAK) in the late forties.

In the USA, Libby initiated the so-called project SUNSHINE in 1953 (Rand Corporation 1953). Its purpose was to critically re-examine the potential hazards from radioactive fallout – in particular ^{90}Sr – that might result from a large scale nuclear test programme including thermonuclear weapons or nuclear war. In the early fifties the US Atomic Energy Commission also initiated other radioecological activities which among others involved well-known radioecologists such as Wolfe, Odum and Aurbach (Nelson and Evans, 1967).

In the following I begin with summarising the major milestones in radioecology over the last five decades. Then I consider the state of the art and finally I shall try to see into the future.

Past milestones

Global fallout

According to the latest UNSCEAR report (2000) 543 atmospheric nuclear test has been carried out. The first test explosion took place in New Mexico (USA) in 1945 and the last in LopNor (China) in 1980. The total fission yield of these tests corresponds to 190 Mt TNT or 741 PBq ^{90}Sr. Of this 115 PBq ^{90}Sr were deposited locally at the test sites (notably Bikini and Enewetak in the Pacific) and 16 PBq decayed in the stratosphere prior to deposition. Hence the total amount of globally deposited ^{90}Sr from nuclear weapons testing became 610 PBq ^{90}Sr. The corresponding global deposition of ^{137}Cs was 930 PBq.

The early nuclear weapons testing with fission weapons (20-100 kilotons TNT range) mainly produced tropospheric fallout, *i.e.* the debris from the explosions remained below the tropopause and was not dispersed globally, but was deposited around the latitude band of the test site. However, in 1952, the USA and, the year after, the FSU tested their first thermonuclear devices (megatons range) and fallout from these explosions occurred worldwide. The distribution of the global fallout shows a maximum around 40 °N and minima at the poles and the equator. The deposition of radionuclides in the Southern Hemisphere is about one third of that in the northern. Furthermore, a seasonal variation is evident. In the northern temperate latitudes, the fallout rate in May-June is 3-4 times that observed in November-December.

The average dose to a member of the world population from nuclear weapon testing is calculated to 3.49 mSv. Most of this dose is due to ^{14}C and will be delivered in the future. For the period 1945-1999 the dose is 0.994 mSv and of this about half is from ingestion, with ^{137}Cs, ^{14}C, ^{90}Sr, ^{131}I and ^{3}H being the main contributors (UNSCEAR, 2000).

The calculation of doses has been based on systematic observation of the relations between deposition of a radionuclide ($kBq \cdot m^{-2}$) and its time-integrated concentrations in diet ($Bq \cdot y \cdot kg^{-1}$). UNSCEAR (2000) has *e.g.* found that the transfer coefficient for ^{137}Cs for a world average diet is 8.4 $Bq \cdot y \cdot kg^{-1}$ per $kBq \cdot m^{-2}$. Taking amount of diet and dose-factor into consideration the dose-deposition coefficient becomes: 55 μSv per kBq ^{137}Cs m^{-2}. It is, however, evident that such a coefficient will show variations due to individual food habits and environmental conditions. For the same diet type *e.g.* cow-milk the transfer coefficient for ^{137}Cs thus vary by an order of magnitude according to environment. In other words some environments may be ten times more sensitive to contamination (of cow-milk) than others; we say the *radioecological sensitivity* differs by a factor of ten (Aarkrog, 1979).

Some population groups received relatively high doses from global fallout. This was the case for some arctic and subarctic populations that herd and breed reindeer and caribou (Lidén, 1961; Miettinen *et al.*, 1963; Hanson *et al.*, 1964; Ramsaev *et al.*, 1965). Maximum concentrations of ^{137}Cs in these population groups were more than 50 times higher than the human body levels found in general in the Northern Hemisphere in 1964-1965 (UNSCEAR, 1966). The reason for the high ^{137}Cs levels in reindeer and caribou was the consumption of lichen by these animals.

Nuclear reprocessing

From a radiological point of view nuclear reprocessing has so far been the major source to the ingestion dose from the nuclear fuel cycle. Most of this dose has come from authorised discharges to the sea of ^{137}Cs from Sellafield in the UK in the seventies and early eighties (UNSCEAR, 2000).

The collective effective dose from Sellafield derived ^{137}Cs (~ 40 PBq) has been calculated to be approximately 4000 man·Sv, corresponding to an individual average dose to the world population (6×10^{9}) of 0.7 mSv or a transfer coefficient of 100 man·Sv per PBq ^{137}Cs. Local population groups living near the Irish Sea with a high consumption of fish may back in the seventies, have received annual doses in the order of the natural background (Hunt and Jefferies, 1981).

Chernobyl accident

Several radioecological lessons were learned after the Chernobyl accident in 1986. We saw the importance of natural and seminatural ecosystems when it comes to intake of radiocaesium with human diet. It became evident that the contamination of mushrooms by radiocaesium was one of the important pathways in such ecosystems. For example, a strong seasonal variation of ^{137}Cs in roedeer was demonstrated in Sweden (Johanson *et al.*, 1990). This variation was mainly due to consumption of mushrooms in the autumn. In Scandinavia, the lichen-reindeer-human foodchain was another major pathway. This was in agreement with expectations from the global fallout studies mentioned above.

Another observation told us that the relative composition of the fallout from a reactor accident may change with the distance from the reactor. It was thus observed that the ratios $^{90}Sr/^{137}Cs$ and $Pu/^{137}Cs$ decreased significantly with the distance from Chernobyl.

The accident furthermore taught us the importance of seasonality. Thus crops in southern Europe showed higher radiocaesium concentrations than crops from northern Europe for the same deposition density of ^{137}Cs. The reason was precocity of southern crops compared to northern.

From the Chernobyl accident about 85 PBq ^{137}Cs, 54 PBq ^{134}Cs, 1760 PBq ^{131}I, 10 PBq ^{90}Sr and 0.07 PBq $^{239,240}Pu$ were released together with many shorter-lived radionuclides of less radioecological significance. One of the more serious late effects of the Chernobyl accident has been the approximately 1800 thyroid cancer cases reported in the FSU in children and adolescents for the period 1990-1998. A major radioecological task in the future is a reconstruction of the ^{131}I deposition to make an assessment of the individual doses to these population groups. This may be done by measurement of ^{129}I in the affected areas, but ^{137}Cs deposition data may be a usable alternative.

Apart from the thyroid doses from ^{131}I the total collective effective dose to the population in the most contaminated areas in the FSU (> 37 kBq ^{137}Cs m^{-2}) has been calculated to be 60 700 man·Sv (UNSCEAR, 2000). This dose is mainly due to ^{137}Cs (36 125 man·Sv from external exposure and 13 207 man·Sv from ingestion of ^{137}Cs). The total deposition of ^{137}Cs over this area in the FSU was 29 PBq. This give us a transfer factor of 1700 man·Sv per PBq ^{137}Cs.

Summary

Three events have been the main contributors to the exposure of the global population from man made radioactivity.

- Global fallout from nuclear weapon testing;
- Liquid discharges from nuclear reprocessing;
- The Chernobyl accident.

These events have furthermore been main objects for radioecological studies over the last fifty years.

A way to summarise – in a very condensed and subjective way – the outcome of these fifty years of radioecological studies could be to show a table with the transfer coefficients for ^{137}Cs derived from these studies.

Whereas the doses from nuclear reprocessing comprise only the marine environment the two other sources deliver their doses through both the terrestrial and marine environments. Had we for global fallout and the Chernobyl accident considered only the terrestrial environment the ingestion dose transfer factors for these two sources would have increased to 3 and 0.5 respectively, because the transfer coefficients between diet concentrations and deposition are less in the marine than in the terrestrial environment and thus "dilute" the transfer coefficients in Table I.

Table I. Collective dose transfer coefficients.

Source	man·Sv per TBq ^{137}Cs Total dose	 Ingestion dose
Global fallout	3	1
Nuclear reprocessing	0.1	0.1
Chernobyl accident	1	0.4

Present situation

Introductory remarks

Two years ago Murdoch Baxter, the editor of Journal of Environmental Radioactivity asked the members of the Editorial Board to contribute to a series of millennial editorials which should reflect thoughts on problems related to environmental radioactivity by the entrance to the new millennium/century.

These editorials may give a fair general view of the actual state of the art of radioecology. The members of the editorial board are in this context considered representative of the radioecological science as it has developed until now. In the following I shall try to summarise some major trends from these editorials.

Outlook

It is a general opinion among many of the authors (Scott, 2000; Voigt, 2000; Ohmomo, 2000; Whicker, 2000; Woodhead, 2001; Holm, 2001) that the present situation for radioecology looks less promising. The reasons for this are several. Radioecology is strongly dependent on the development of the nuclear option for energy production. In most countries, the public opinion has for several years been against the use of nuclear energy and the Chernobyl accident became the deathblow. One may argue that if people are so afraid of radioactivity they should be in favour of a discipline such as radioecology which improve our understanding of the risks and also develops methods to mitigate environmental contamination. But this is apparently not the case. At most radioecology is considered as a necessary evil in particular in the wake of nuclear accidents. Now fifteen years after Chernobyl it seems difficult to obtain the necessary funding for a continued fruitful development of radioecology. (Scott, 2000; Whicker, 2000).

The remembrance is short – in particular among politicians. We should, however, not forget to sweep before our own doorstep. One of the lessons learned after Chernobyl was also the very short memory of radioecologists or rather the lack of interest in using old experience by reading the literature. So a new generation may often reinvent the wheel perhaps in order just to get started. It is always a little frustrating for a scientist to learn that somebody was there before he/she arrived!

New technologies

But what do we do then? New technology has given radioecology – as any other science – possibilities which we fifty years ago could only dream about. But this also involves a risk. Modern computers can do nearly anything and they have been a tremendous step forward also when we try to analyse and model the behaviour of radionuclides in the environment. We should, however, never forget that any model should be based on reliable measurements if we wish it to mimic real life. An old expression says: garbage in – garbage out. This is also the case even for the most advanced and sophisticated Information Technology.

Instrumentation (solid state detectors and various mass spectrometers) for measuring the often very low concentrations of radionuclides in the environment has become widely accessible during the last decades. Today we can measure even very tiny and, from a health perspective, completely insignificant concentrations of radionuclides. Although we, from a scientific point of view are welcoming this, we should not ignore the reverse of the medal: if an environmental contaminant is measurable then it – for some people – is a proof that our environment is polluted and that we have to get rid of the source of this "pollution". This belief has probably been one of the major reasons for people's worry for radioactivity- which is so easy to detect even in insignificant quantities. "Do not measure simply because it is possible!!" as Scott (2000) puts it.

Models

So today we can model and measure the behaviour of radionuclides in our environment and are thus at least in theory well prepared to handle nearly any release of radioactivity. I may here be too optimistic, but it does not seem likely to me that we could envisage a situation where we, due to lack of radioecological knowledge, were unable to protect man adequately against significant exposure from environmental radioactivity.

This is of course not the same as saying that such exposures could not occur. We saw it for instance after the Chernobyl accident. The occurrence of thyroid cancer was, however, not due to missing radioecological knowledge, but to socio economic problems in the FSU.

I am neither saying that radioecological models do not need improvements. "Appropriate research in radioecology can do much to reduce the uncertainty and increase the credibility of dose assessment models" as Ward Whicker (2000) rightly reminds us.

Tracer studies

From what has been said above it is obvious that radioecology would benefit from having a broader perspective than just that connected to the nuclear option. One of the more successful applications of radioecological methods have been tracer studies. The large injections of radionuclides from nuclear weapons testing, reprocessing and the Chernobyl accidents has made it possible to study many atmospheric, aquatic and biological processes.

One may, for example, mention the application of ^{99}Tc and ^{129}I – both radionuclides of little radiological significance – in the studies of the transport and dilution of pollutants in the NE-Atlantic including Arctic waters (Woodhead, 2001). Another example is the use of tracers (^{137}Cs) to estimate feeding rates under natural field conditions (Whicker, 2000). This can be applied at an early stage to detect external stress in *e.g.* fish populations exposed to chemical pollutants.

Other pollutants

In general radioecology would undoubtedly benefit from being recognised as a usable discipline in the studies of environmental pollution problems. The present congress could be an important vehicle for such an improved co-operation and understanding between radio- and chemoecology. In this context Polikarpov (2001) has suggested to make a comparative ecological equidosimetric assessment on the basis of Gy/y and Sv/y for physical, chemical and biological contaminants.

Another aspect in this connection is the study of synergistic or antagonistic effects between different pollutants (Voigt, 2000). UNSCEAR (2000) has recently dealt with the combined exposures to radiation and other agents with respect to the induction of stochastic effects at low doses. With the exception of radiation and smoking UNSCEAR concludes that there is little indication from epidemiological data of strong antagonistic and synergistic combined effects. From a radioecological point of view one may ask if we could imagine that the behaviour of radionuclides in an environment would be influenced by the level of environmental contamination *e.g.* with chemical pollutants. Such studies have been proposed in the FSU.

Other species

The so-called "redforest" of radiation damaged trees observed in the nearzone of Chernobyl has perhaps been the inspiration to develop protection standards targeted specifically to plants and animals (Scott, 2000; Whicker, 2000). ICRP (1977, 1991) has assumed that if man is adequately protected from environmental radioactivity then other organisms can be assumed to be adequately protected as well. Questions have being raised whether this assumption is still valid.

In case of forest systems, Amiro (2000) concludes that doses less than 1 mGy/d^{-1} has little effect on forest organisms, furthermore doses above 1 mGy/d^{-1} will only occur in highly contaminated areas where human activity is limited. In other words, harm to humans is in this case decisive for the dose limits. On the other hand, it is known that dose rates well below 1 mGy d^{-1} can produce chromosome damage and Whicker (2000) is asking whether chronic dose rates below 1 mGy d^{-1} affect the ultimate viability of long-lived organisms.

When these discussions earlier have come up – *e.g.* in connection with possible enhanced radiation exposure to deep sea organisms from dumped rad-waste – it has been argued that although individuals may be at risk, the natural selection will ensure that populations are preserved. Nevertheless it has been concluded by IAEA (1999) that there is a serious need to develop defendable primary dose rate criteria for protection of the environment. This will require new knowledge on the transport, dosimetry (Kocher and Trabalka, 2000) and ecological effects of radionuclides in the environment (Alexakhin, 2000).

Countermeasures

A major task – also for radioecology – in recent years has been the development of countermeasures (Scott, 2000; Voigt, 2000; Ohmomo, 2000; Wilkins, 2000; Whicker, 2000) to mitigate the effects of environmental contamination from accidents and at dismantled nuclear sites. In this connection the socio-economic effects and ethical aspects have added a new dimension to the obligations of the radioecologist (Polikarpov, 2001). Any method to clear land from radioactive contamination should not only be economic and technical feasible, but should also be accepted and understood by the people affected by such measures.

Information and education

This leads me to our educational and informative obligations. Baxter (1999) has mentioned the need for information and education. It is a deplorable fact that although radioecology has been in existence for half a century, we have not succeeded in explaining to the public the implications of radioactive contamination of the environment. Many people still think that amongst all pollutants the radioactive ones are the most hazardous irrespective of their concentrations and occurrence.

We are also obliged to involve scientists from the developing countries in our research. A mutual co-operation might be of benefit to both parties. The developed world would gain an opportunity to work in ecosystems, which are "terra incognito" to most radioecologists. The developing countries would for their part gain access to modern techniques and learn how to carry out radioecological studies so that these turned into more than just monitoring exercises.

Research

The majority of radioecological research has so far been based on field observations of environmental radioactivity. Experiments in the laboratory or in well-defined controlled experimental environments are less frequent. Hinton (2000) has – based on an old article in Science (Plat, 1964) – pleaded for a more hypothesis-oriented radioecological research. To quote Plat: "we measure, we define, we compute, we analyse, but we do not exclude", and further we become "method-oriented" rather than "problem-oriented". I agree, and hope with Hinton that more of the radioecological research in the new millennium/century will develop in an experimental direction, where we will test hypothesis rather than just describe what we observe.

Concluding remarks

Although many radioecologist may be worried for the future I have in the millennium editorials also noticed a general optimism. Radioecology has a good chance of survival in the next millennium because it is one of the most fascinating environmental sciences, one in which we see a fruitful interaction between the main scientific disciplines: mathematics, physics, chemistry and biology and all the sub-specialities such as meteorology, oceanography, geology, botany, zoology, physiology and statistics. Radioecologists have very different background and this makes the scientific dialog and co-operation challenging and inspiring. Hence, I think it is desirable that radioecology survives and develops, not necessarily because society finds it environmentally required for utilisation of the nuclear option, but because it is a promising and challenging environmental science.

Future trends

Crystal ball gazing does not belong to any of the scientific disciplines mentioned above. So what is said in the following may be considered as pure fiction and no references to scientific journals will be provided. Bio- and information-technology will in the new millennium influence all sciences dramatically – radioecology being no exception. Gene therapy and "smart" molecules will be developed to prevent many diseases including cancers. Hence, radiation protection will first of all be concentrated on avoidance of deterministic effects and the need for preventing stochastic effects will become less pertinent. This will probably change the whole philosophy of ICRP. The non-threshold concept may be quit and concern for

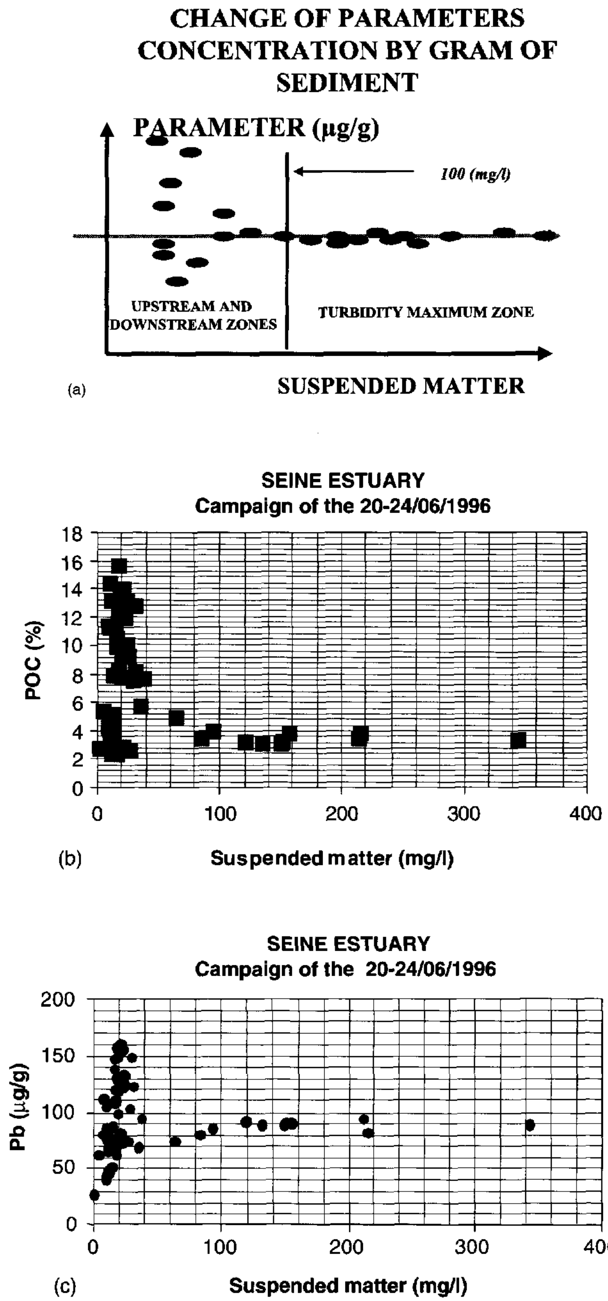

Figure 13.10 (a) Seine Estuary: evolution of concentrations of particulate organic carbon (b) and lead (c) as a function of the levels of suspended matter, (based on Chiffoleau *et al.* (2001)). Demonstrates a certain homogeneity of concentrations in the particulate phase beyond 100 mg/l de SM.

- the turbidity maximum stores and eliminates contaminated sediment, depositing pollutants on the estuary floor and/or in subtidal and intertidal marshes. They will no remove except as a result of anthropogenic activity (dredging). The estuary **filters** inputs to the sea;
- for contaminants which behave as dissolved compounds, like lindane, atrazine, and simazine, until they are gradually diluted by seawater which is theoretically exempt from contamination, fluxes to the sea are similar to fluxes entering the estuary. Here, the estuary's role as a **transparent medium** is evident. Of course, intra-estuarine input clouds the picture;
- lastly, let us point out a less obvious purpose of the macrotidal estuary as a **regulator** of flux. The gradual increase of the water volume and the presence of the turbidity maximum can significantly lengthen the amount of time dissolved and particulate pollutants remain in the estuary. When upstream emissions peak due to an accidental spill or flooding, they can attenuate and absorb excesses.

4. Chemical hazards for the estuarine ecosystem

4.1. The approach to chemical hazards

European legislation on chemical pollutants requires increasingly accurate information on concentrations found in the environment, especially in aquatic systems. We have already mentioned the unique nature of the estuary, in terms both of its special dynamics and conditions, and of its geographic location at the mouth of catchments.

New European Union directives will demand more precise data about quality of hydrosystems, and it must be acknowledged that few tools ar now available enabling them to predict chemical pollutant concentrations (expressed by the EU as PECs, Predicted Environmental Concentrations) on a site-specific basis. According to the legislative policy guidelines, the PEC will be compared to concentrations which have no biological effects on the system, known as PNECs (Predicted Non-effect Concentrations). For example, industrialists likely to dump chemical pollutants into a river must take the measures necessary to reduce their emissions in such a way as to respect a PEC/PNEC ratio < 1.

What about the estuarine system? Will it be possible to enforce this policy, considering the complex characteristics and specificity of this environment?

Any approach to risk analysis must take the following two concepts into consideration:

- the first concerns randomness; *i.e.* the **probability** that a phenomenon likely to damage the natural environment will occur;