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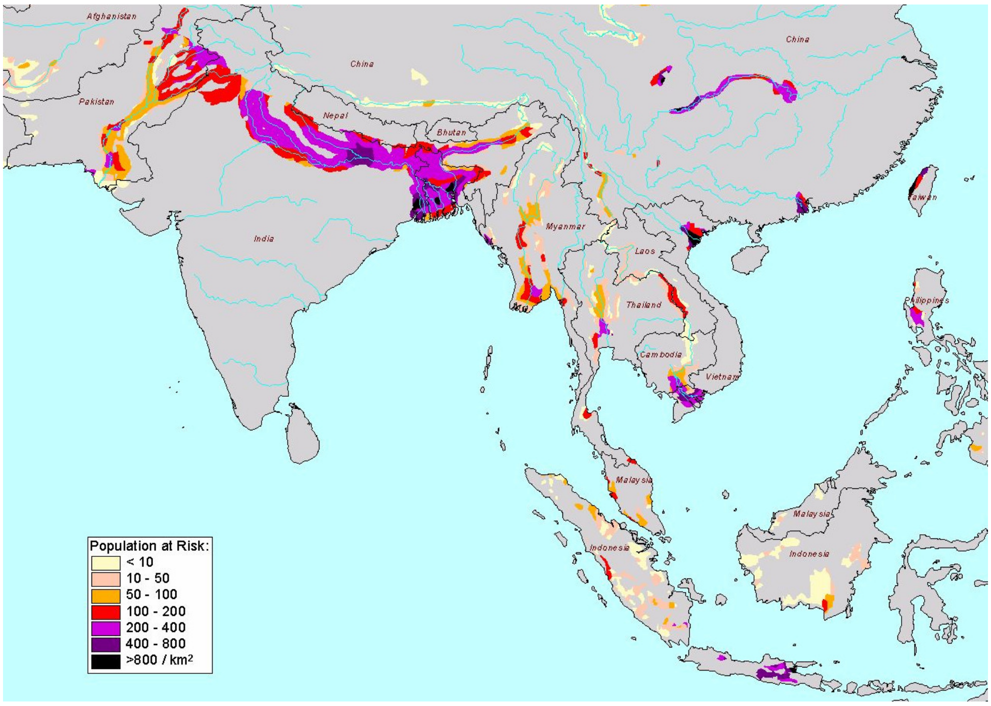
PREDICTING THE GLOBAL EXTENT OF ARSENIC POLLUTION OF GROUNDWATER AND ITS POTENTIAL IMPACT ON HUMAN HEALTH



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PREDICTING THE GLOBAL EXTENT OF ARSENIC POLLUTION OF GROUNDWATER AND ITS POTENTIAL IMPACT ON HUMAN HEALTH

UNICEF FOREWORD

This report was prepared by a consultant to UNICEF, Mr. Peter Ravenscroft, based on his extensive research at the University of Cambridge into known worldwide incidences of arsenic contamination of groundwater and resulting arsenicosis.

The consultant developed a model to predict areas where there is a risk of arsenic in groundwater based on the Geographical Information System (GIS) database of Environmental Systems Research Institute (ESRI). Selection of the geo-climatic environments where there is a risk of arsenic in groundwater was based on published peer-reviewed literature concerning known occurrences of arsenic in groundwater.

The model predicts potential for occurrence of arsenic in groundwater. The prediction is tentative and an attempt has been made to indicate the level of scientific confidence in the prediction country by country. Predictions of country-wise population *at risk* were made using ESRI population density data for potentially affected areas. It has not been determined whether the population living in these areas is in fact consuming groundwater and, in the event that groundwater proves to be contaminated with arsenic, would thus be *exposed*.

In addition, we know from empirical evidence from arsenic-affected countries, such as Bangladesh and India, that distribution of arsenic in the sub-surface is very variable. Only a certain percentage of sources in any arsenic-affected area will be found to be arsenic-contaminated, whereas conversely a certain percentage will be found to be arsenic-safe. The implication is that only a proportion of the *at risk* population will be actually *exposed*, that is, drinking arsenic-contaminated groundwater on a daily basis.

This distinction between population *at risk* and population *exposed* is important. It must be understood that the figures given in this report are predicted populations *at risk*, whereas the population actually *exposed* may in reality be much less. **It is important to read the report with this in mind.**

With these caveats properly understood, UNICEF considers this report to be an excellent piece of investigative modeling which uses the available GIS database in a powerful predictive manner. It has been prepared as a tool for UNICEF staff members in their countries of operation as a starting point for further consideration of the risks to public health posed by exposure to arsenic from groundwater used for drinking. In some countries further investigations such as desk studies of available data and/or testing of groundwater for arsenic will definitely be merited. Where this is the case UNICEF will lobby for action by the national government and provide support, advice and expertise in all aspects of investigation of arsenic risk and mitigation of the effects of arsenic if they are found.

With the assistance of UNICEF Bangladesh and India country offices, where UNICEF has built up considerable expertise in arsenic investigation and mitigation, UNICEF New York is currently developing a short manual intended to assist country offices in designing and implementing programmes to tackle the problem of arsenic contamination of groundwater used for drinking. The ‘Arsenic Primer’ will be available early 2008 and should be consulted alongside this report.

EXECUTIVE SUMMARY

Natural arsenic pollution of groundwater and surface water affects more than 140 million people in at least 70 countries worldwide. In half the countries where arsenic pollution is now known, it was discovered within the last ten years, and it is almost certain that it will be found in many more. The objective of this study is to predict the other countries and regions in which there is a significant risk of finding arsenic pollution.

By examining known arsenic occurrences, their geochemistry, and their climatic and geological associations, it has proved possible to develop a set of predictive rules that have been embodied in a GIS model. This model not only predicts the locations where there is a risk that groundwater is polluted by arsenic, it also estimates the population of the 'at risk' regions, and hence provides a basis for predicting the size of the population which may be exposed to drinking arsenic above the WHO guideline value and/or local standards. The GIS model does not predict all known forms of natural arsenic pollution, but based on known occurrences, is expected to predict more than 90% of them.

The GIS model has been applied to the whole world, and this report provides maps of the at-risk areas and listings of the at-risk population in each country. The model successfully predicts the vast majority of the major known cases of pollution. The model predicts a risk of arsenic pollution in 54 countries where pollution is known to occur, and also in a further 53 countries where it is not known. Nine countries, with large at-risk populations but no reported cases of pollution, have been selected for more detailed mapping. These countries were chosen to represent a range of conditions and include four in Asia (Indonesia, the Philippines, Iraq and Uzbekistan), two in South America (Colombia and Venezuela) and three in Africa (Ethiopia, Sudan and Morocco).

Where a risk of arsenic pollution is predicted, relevant courses of action are recommended. In countries where arsenic is a familiar problem, it may be sufficient to provide guidance for additional surveys. Where arsenic pollution is predicted but not known, a second tier of desk study is recommended to evaluate the model predictions in the light of national data sets and, provisionally, to identify areas, personnel and testing protocols for field surveys.

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1 Introduction

1.1 Background

Natural arsenic pollution[1] of groundwater and, to a much lesser extent, surface water, is known to have exposed more than 140 million people to arsenic (As) concentrations of more than 10 µg/L (the WHO guideline) in at least 70 countries as shown in Figure 1 and listed in Appendix I. The resulting arsenic poisoning has caused death and disease in huge numbers. Until recent decades, arsenic poisoning was regarded as an obscure or local phenomenon, however, it is now recognised to be a global problem. In around half the countries where arsenic is known, pollution was discovered within the last ten years. This alone suggests that more cases will be identified, and geological reasoning strongly reinforces this. Far, far too many cases were discovered either by accident or by investigating the causes of disease. The proposition of this study is that the majority of locations where there is a risk of arsenic pollution can be predicted, albeit that pollution may actually not be found in all the predicted locations.

This study was undertaken in line with terms of reference issued by UNICEF, New York, and involved three main components:

(i) *Contributions to an "Arsenic Primer".* Contribute to an 'arsenic primer' being prepared by UNICEF staff arsenic experts, which is envisaged to be a practical manual for project officers and partners that explains the sources and extent of arsenic in groundwater, and practical steps to take if arsenic is discovered.

(ii) *Annotated list of countries where arsenic contamination of groundwater is expected*, accompanied by appropriate maps, and including details of specific areas within countries and the expected reasons for arsenic occurrence. The document is intended to assist NY HQ and the regional advisors to focus advocacy for arsenic screening, and to complement the 'arsenic primer'.

(iii) *Methodology for estimating 'at risk' populations* within at least five defined risk areas where the population may be exposed to drinking arsenic above the WHO guideline value of 10 µg/L and any local standard e.g. 50 µg/L, after allowing their known or likely water sources and any initial data available on arsenic in groundwater.

Item (i) is reported separately. In reading this report, it is important to appreciate that the models predict the population of the areas where there is a risk of arsenic pollution, and not the size of the population exposed to arsenic in water.

1.2 Scope and Purpose

The overall objective of this study is identify where previously unrecognised arsenic pollution of groundwater, actually or potentially, affects humans, and to place quantitative limits on the numbers of people who may be affected, now or in the future. The models presented here do not predict specific concentrations, but based on experience of other affected countries, these areas are predicted to have significant proportions of wells containing more than the WHO guideline value (10 µg/L), and probably

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[1] This report follows Chapman (2007) in using the term contamination to describe the presence of a chemical that is above natural background concentrations, but pollution describes concentrations that are actually or potentially harmful. Thus, all pollution is contamination, but not all contamination is pollution.

more than 50 µg/L. In fact, in the majority of areas where a significant percentage of wells exceed 10 µg/L, groundwater also exceeds 50 µg/L (Ravenscroft et al., 2008). This should not be seen as a serious constraint on the models because in almost all affected areas concentrations vary by several orders of magnitude over short distances.

The models described here are global, strategic tools. While all models can always be improved, there are serious limits to how far anyone should try to improve these models. Their purpose is to trigger more detailed, national or regional studies using different sources of information, or to initiate field investigations. Probably in every case where an unconfirmed arsenic-risk is predicted, a second-tier of desk study should be undertaken before conducting field surveys. Thus, while it would be reasonable to try to improve the conceptual basis of the global models if it might lead to identifying different areas, it would probably be pointless if it only improves their spatial or numerical definition.

As a basis for a predictive model, the occurrence of arsenic pollution is reviewed in terms of its geological and climatic associations. Predicting all forms of arsenic pollution in all geological settings is impractical, but based on the observation that more than 90% of persons exposed to arsenic pollution draw water from alluvial aquifers, and that in these settings, arsenic is predominantly mobilised by just two mechanisms (alkali-desorption and reductive-dissolution), it should be possible to predict the location of the large majority of the worst As-pollution cases.

GIS models are developed to predict where arsenic pollution may occur. The 240 cases of As-contamination from over 70 countries provide grounds for judging their validity. A predictive model is also put forward for the risk of As-pollution from sulphide-oxidation in bedrock aquifers, although this model has a less satisfactory conceptual basis and lacks data for adequate calibration. It is applied here, but with less confidence than the alluvial model. A predictive model for pollution in glacial aquifers was considered, but was not found to be helpful.

The concept of predicting As-risk in alluvial aquifers has a sound empirical basis, because alluvium is the most important type of aquifer in the world, normally being the shallowest, cheapest and easiest to exploit. For these reasons, they are also very widely exploited for private drinking water and irrigation supplies, but this also explains why the populations that use them have been so vulnerable to arsenic pollution.

1.3 Acknowledgements

The ArcView® GIS software and ArcAtlas®data were accessed during the course of a research project conducted in the Department of Geography, University of Cambridge, UK. The GIS analysis presented is new and original, but is founded on the data compilation and evaluation conducted for a forthcoming book (Ravenscroft et al., 2008). The support of the Geography Department and Professor K.S. Richards is gratefully acknowledged.

2 Scientific Basis of the Model

2.1 Geochemical Mobilisation Mechanisms

The mobilisation of arsenic into groundwater can be generalised in terms of four basic geochemical mechanisms, each associated with particular chemical characteristics, and each occurring in distinctive geological and climatic associations:

Reductive dissolution. Arsenic adsorbed to iron or manganese oxides is released into solution when the oxides, which usually occur as coatings on aquifer sands, dissolve due to microbially mediated reduction. These near-neutral-reducing (NNR) waters are characterised by pH 6.5-7.5, and indicators of strongly reducing conditions such as high concentrations of iron, manganese, bicarbonate, ammonium and methane gas, and an absence of oxidised species such as nitrate and sulphate. Examples include the Bengal Basin (e.g. McArthur et al., 2004), the Mekong and Red Rivers in Asia (Berg et al., 2006), and the Danube and Po in Europe, the mid-west of the USA (Kelly et al., 2005). The processes require the presence of abundant organic matter.

Alkali desorption. Laboratory studies show that arsenic adsorbed to iron, manganese and aluminium oxides and clay minerals may be desorbed at pH >8.0, leaving the carrier phase as a solid. Although some authors (e.g. McArthur et al., 2004) have questioned how widely this occurs in nature, many cases of arsenic pollution have been attributed to alkali-desorption (AD). The best-documented example comes from the southwest USA (Bexfield and Plummer, 2003), and others come from Oklahoma, Spain, China and from volcanic deposits in Argentina (e.g. Nicolli et al., 1989).

Sulphide oxidation. Oxidation of arsenic-rich pyrite and other sulphide minerals is a well-known cause of pollution around mining sites, but is relatively rare in natural systems. However, these processes may occur wherever the water table fluctuates across a sulphide-rich layer, such as in Palaeozoic sandstones in Wisconsin (Schreiber et al., 2000) and Holocene alluvium in Perth, Australia (Appleyard et al., 2006).

Geothermal arsenic. Some of the highest known natural concentrations of arsenic occur in hot springs on the Qinghai-Tibet plateau that originate through high-temperature leaching of rocks, due to either deep and rapid circulation of groundwater or shallow volcanism (Webster and Nordstrom, 2003). In most cases, the contamination risk is suggested by the high temperature, however, severe pollution of rivers and groundwater in Chile results from seepage of geothermal in the Andes, hundreds of kilometres from the point of abstraction (Smith et al., 1998).

2.2 Geological and Climatic Setting

If the distribution of arsenic pollution is considered in terms of the exposed population rather than pure geological or geochemical diversity, some simple and important patterns become clear. More than 90% of all people exposed to drinking water containing >10 µg/L As obtain this water from alluvial aquifers. Most of these basins are what are termed foreland basins, draining and lying adjacent to young mountain belts. In approximately 80% of these cases, arsenic was mobilised to groundwater by reductive dissolution, and in 15% of cases by alkali-desorption. RD occurrences are concentrated in humid environments where organic matter readily accumulates, whereas AD occurs preferentially in hotter and drier environments. It has also been shown that the occurrence of As-contaminated alluvial aquifers is correlated with characteristics of river basins such as their sediment load and mineralogy, and the chemistry of river water (Ravenscroft et al., 2008). These latter characteristics are important, and are related to the geochemistry of groundwater, because they determine the supply of slightly weathered sands containing a source of mobilisable arsenic adsorbed to iron oxide coatings. The climatic influence determines whether this can be mobilised by reduction or desorption.

2.3 Population: Exposed and At-Risk

Accounts of arsenic pollution are often confused by the vague of differing uses of the terms 'populations at-risk' and 'exposed population'. In the absence of internationally accepted definitions, it is important to define the terms used in this study:

- The **exposed population**, should be the most straightforward to define, as the number of persons drinking water containing more than the relevant concentration threshold, and yet even this poses problems. It may be defined as either the legal standard for the particular country or the health related guideline issued by the WHO (10 µg/L). Where groundwater irrigation is important, this introduces a second source of exposure. In addition, there is also a question of present and past exposure, because of the extreme latency of the carcinogenic effects of arsenic (e.g. Yuan et al., 2007), all those people who have been exposed to high arsenic concentrations within the past two to three decades face highly significant risks of developing fatal cancers.
- Defining the **at-risk population**, inevitably involves more arbitrary judgements. First there are the classic problems of predicting the boundaries of affected areas and of knowing what percentage of water sources are affected. Second, there is sometimes confusion regarding the nature of the risk – whether there is a risk of exposure to significant concentrations of arsenic in food or water (and of course, at what concentration) or whether there is a risk of developing arsenicosis. The number of people who develop arsenicosis will be only a small proportion of the people who consume more than the maximum recommended levels of arsenic. Nevertheless, these problems in no way prevent practical working rules being applied.

Apart from location, the models predict the population of the areas within which there is a risk of arsenic pollution of groundwater. In the models, population densities from low-resolution data sets are applied to known areas with a particular geological and climatic association. There is inherent imprecision, but not fundamental error, in this method. Even if arsenic is present in groundwater, the population actually exposed to drinking (or eating food cooked in) such water will be significantly less, and may sometimes be close to zero. In this context, it is useful to distinguish between an actual and a potential health hazard. There is a hierarchy of reasons why the exposed population will be less than the at-risk population:

1. Special geological conditions may have prevented arsenic mobilisation, or attenuated it, in a location that otherwise appeared favourable to mobilisation.
2. Groundwater may not be used for water supply. In alluvial tracts, this tends to occur either in areas of low population density where there is little pressure on, or pollution of, surface waters; or in urban and peri-urban areas where a municipal supply is piped into the area. The latter situation is particularly prone to over-inflating the at-risk estimates.

3. Groundwater is rarely pervasively polluted. Although there are parts of Bangladesh, for example, where nearly all wells are polluted, in most affected regions only a few tens of percent of wells that are polluted. The proportions often vary with well depth and may well change over time with growing knowledge.
4. Some part of the groundwater used may be drawn from deeper alluvial, or even non-alluvial, aquifers that are not affected by arsenic. Indeed, deeper alluvial aquifers are often valuable solutions.
5. Groundwater may be directly treated, or indirectly treated by way of storage prior to use, so that concentrations measured at the well-head are not actually experienced by consumers. This is particularly common in the case of aeration to remove iron and/or odour problems, which removes at least part of the arsenic as an unintended benefit.

The at-risk populations predicted by the two GIS models are not perfectly compatible because the main, alluvial, model is based on objectively defined geographic boundaries whereas the sulphide-oxidation model uses arbitrary boundaries. Also, the aquifers in which the SO model predicts pollution are likely to be low-permeability fractured rock, and hence greater use of other water sources inherently more likely.

Improving the population estimates requires first a more detailed map of population (which would, for instance, increase the at-risk population in Bangladesh to around 100 million), and second national, or better, regional statistics on water use and access to different water supply. However, there is a major caveat here, in areas where arsenic has not been detected, statistics reported as ‘access to improved water supplies’ will include wells that are polluted by arsenic.

2.4 Prediction Principles

The objectives of the model are to identify where sources of slightly weathered sand, containing As-bearing igneous and metamorphic rock fragments accumulate to form aquifers, and classify these depositional environments according to whether reducing or oxidising geochemical processes operate there. The favourability of these processes can be crudely predicted from annual rainfall and temperature statistics.

Conditions that favour delivery of relatively unweathered sand to the lower catchment are a cool and high altitude upper catchment where there is little chemical weathering, and a steep river profile (as expressed in high sediment load) so that there is limited modification during transport. Young mountain belts formed at destructive plate margins, such as the Alpine-Himalayan and Rocky-Andean chains, provide a good source of igneous and metamorphic rocks and hydrothermally enriched sediments with moderately, but not remarkably, arsenic-enriched content. The ArcAtlas™ GIS database (ESRI, 1996) contains global mapping of mountain belts (geosynclines) and Quaternary sediments. These themes can be linked through mapping of the river channels to classify which alluvial deposits are derived from these mountains. ESRI’s Quaternary sediment mapping also identifies volcanic sediment, normally originating from the same mountain sources, which is a significant risk factor for arsenic pollution (e.g. Argentina). In addition, it is recognised that aquifers within or immediately adjacent to young mountains or volcanoes may also be contaminated by arsenic from geothermal sources.

The ArcAtlas™ database also contain climatic and demographic information. The former data can be used to predict the most likely arsenic mobilisation mechanism, and the latter to classify the map units according population density and country. The correlation between processes and present climate will be imperfect because climates may have different in the geologically recent past, when the aquifer sediments were deposited. This may account, for example, in abundant organic matter in areas that have low rainfall. Consequently, the map units are qualified as 'high' or 'low' risk according the likelihood of AD or RD being the dominant mechanism.

A second line of predictive evidence derives from studies of the mineralogy of suspended sediment and the chemistry of river water in arsenic-affected river basins (Figure 2), and discussed in detail elsewhere (Ravenscroft et al., 2008). The intensity of chemical weathering, and hence removal of arsenic, is reflected in increasing proportions of quartz in sand, and silica in river water. Basins where arsenic pollutes alluvial groundwater have a characteristic grouping, and it is reasonable to assume that a similar chemistry is a risk factor for arsenic in basins where its status is unknown.

3 Formulation of Predictive Models in Geographical Information Systems

3.1 Arsenic Risk in Alluvial Aquifers

Following the principles described above, a GIS model was formulated in ArcView using the ESRI (1996) data set, as described below and a flowchart of the data processing methodology is shown in Appendix II.

1. Classify Quaternary as 'alluvial' by 'Type' = alluvial, lacustrine or fluvio-glacial [([Type] = 3) or ([Type] = 4) or ([Type] = 6) or ([Type] = 11) or ([Type] = 30) or ([Type] = 34) or ([Type] = 35) or ([Type] = 36) or ([Type] = 42)]. These are alluvial, lacustrine, fluvioglacial, volcanic, alluvial and deluvial, lacustrine-alluvial, lacustrine-glacial, alluvial-marine and volcanic-sedimentary. Based on knowledge from Argentina, loess ([Type] = 11) was added for South America only because this is known to be rich in volcanic ash and to be a major cause of As-pollution. 'Proluvial' alluvium ([Type=37]) was also introduced later for all areas.
2. Classify average annual rainfall as <500, 500-1,000, 1,000-1,500, and >1,500 mm (rain_class = 0, 1, 2, 3).
3. Intersect the rainfall theme on the 'alluvial' theme, and classify alluvium by rainfall class
4. Classify average annual temperature as <10, 10-15 and >15°C (temp_class = 0, 1, 2), assigning the results to the alluvial polygons.
5. Combine <rain_class> with <temp_class> to generate a <Climate_class> field as per Table 1. A sub-humid class was defined to include areas with 500-1,000 mm and annual temperature of < 10°C, which empirical evidence suggested had similar favourability for arsenic mobilisation to 500-1,000 mm at temperatures of >10°C.
6. To identify rivers likely to carry sediment likely to have potential to release arsenic, classify rivers as either crossing or being within 50 km of a Tertiary 'geosyncline' (mountain belt), or are within 50 km of a volcano (note, buffers around volcanoes may require 'clipping' to coincide with the coastline). Manually add downstream channels. A 50 km buffer is created around the young-mountain sourced streams and their downstream channels that are suspected to receive major contributions of water and/or sediment there from. Also include rivers flowing across Quaternary volcanic deposits (Type=11).
7. Intersect mountain-source rivers on the climatically-classified alluvial theme to define the basic AD (<1000 mm), low-RD, and high-RD (>1500 mm) As risk categories. These polygons are refined by intersecting the 50 km river buffer onto the alluvial polygons.
8. Intersect the classified alluvial polygons onto the population density theme. Then repeat the intersection onto the continent theme to assign country names to the polygons.
9. At a continental level, bedrock aquifers in all areas of Tertiary mountains are also considered to be at risk from geothermal arsenic. Use the 'select by theme (intersect)' procedure to classify the alluvial polygons that intersect the Tertiary mountains (plus volcanoes with 50 km buffer) in order to define supplementary geothermal-As risk class.
10. Assign the As-risk according to Table 2.

11. After assigning the arsenic-risk (process) categories, alluvial deposits older than the Upper Quaternary ([Age]<=10) were excluded where mobilisation was predicted to be due to reductive dissolution, in line with widespread experience from Asia.
12. Use the XTOOLS add-in to assign areas, which are multiplied by the population density to calculate the population at potential risk (without knowledge of whether groundwater is used for drinking or irrigation). The population calculation uses the parameters listed in Table 3. Finally the population at-risk estimates are summarised by country.

3.2 Sulphide-Oxidation in Bedrock Aquifers

Globally, arsenic mobilised by sulphide-oxidation represents a much smaller risk than that of RD- or even AD-type mobilisation in alluvium. However, it can be locally severe, and occurs both inside and outside young mountain belts. The method outlined below aims to predict the likelihood of such natural occurrences of arsenic based on the observation that most such cases occur in mining regions even though pollution is not attributable to mining activities. A flowchart of the data processing methodology is shown in Appendix II.

The basic proposition is that arsenic is present as an impurity in Fe, Cu, Zn and Pb sulphides as well as in arsenic-minerals such as arsenopyrite, realgar and orpiment with which they may be associated. It is also well known that arsenic is spatially associated with areas of gold mining in Ghana, Burkina Faso, Chhattisgarh (India), and in Washington State (USA), with copper mining in Chile, silver mining in Mexico, and tin mining in Thailand and Cornwall. An important point here is that the association of arsenic is with sulphide minerals and not the specific element, and hence can be released to water by oxidation (whereas oxide or carbonate minerals would tend to be stable). Therefore the form of mineral deposit is significant, and so deposits produced by sedimentary (e.g. placer gold and many iron ores) of weathering (e.g. bauxite) processes can be rejected. Likewise, ferrous metals, which are mostly resent as oxides and gemstones which are not expected to have causal relationship to arsenic release were rejected. ESRI (1996) produce global data set on mineral resources. Irrelevant materials were excluded as follows:

> ([Group] <> "Ferrous metals") and ([Group] <> "Fuels") and ([Group] <> "Gemstones") and ([Group] <> "Nonmetals") and ([Type] <> "Sedimentary") and ([Type] <> "Weathered").

Within the remaining data-set, the principal element was used to define a potential association with arsenic pollution risk: silver (Ag), gold (Au), arsenic (As), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb), antimony (Sb), and tin (Sn). Only one location, Darrydagskoye, a post-magmatic deposit in Azerbaijan, was mined principally for arsenic. These depsoits were selected:

> ([Main_eleme] = "Ag") or ([Main_eleme] = "Au") or ([Main_eleme] = "As") or ([Main_eleme] = "Cu") or ([Main_eleme] = "Hg") or ([Main_eleme] = "Ni") or ([Main_eleme] = "Pb") or ([Main_eleme] = "Sb") or ([Main_eleme] = "Sn")

It is probably unwarranted to assume that that the nominal size (small, medium, large and very large) of the mineral deposit, which is also a result of the value of the element, reflects the extent of mineralization, and hence an arbitrary buffer size of 30 km was applied. A variable buffer cold be used, but currently there is no theoretical or empirical basis to assign values to the buffers.

To avoid double-counting, all alluvial-risk areas identified by the previous methodology are excluded by an ArcView union operation, following by deletion of the overlapping areas. Because pollution involves oxidation, it was considered that high temperature and/or low rainfall would make pollution more likely.

3.3 Glacial Aquifers

Arsenic pollution of glacial and fluvio-glacial aquifers is well-known in the USA, Canada and Finland, but largely unrecognised in other glaciated regions. Some cases, such as in Alaska, lie within young orogenic belts such as would be (indeed are) predicted by the alluvial model described above. However, the majority of cases come from stable continental regions. Erickson and Barnes (2005) showed that wells drilled on deposits of the youngest glacial advance in the USA (the Wisconsinan) were much more likely to be polluted in Minnesota, Iowa and the Dakotas. In Finland, arsenic polluted groundwater was correlated with arsenic anomalies in glacial sediment (Tanskanen et al., 2004). However, in most countries of interest here, the requisite geochemical atlases probably do not exist, and it would be simpler, and far more reliable, to survey groundwater directly.

The ESRI (1996) database includes mapping and classification of glacial deposits, and these have been compared with the occurrence of arsenic pollution. Unfortunately, even after dividing these deposits by their age does not help greatly to localise the potential risk. These deposits cover the large part of Canada and a continuous swathe of the northern USA from Montana to the Atlantic. It appears that many of the most serious cases of pollution in glacial aquifers are located in buried valleys

Relatively few countries have substantial covers of glacial deposits are likely to come under UNICEF's priority programmes. However, it should be noted that glacial aquifers should be considered suspect, and expert advice sought. This model is not used further here.

4 Discussion of Model Results

4.1 Preamble

Because their aims are to identify areas with unrecognised pollution, such models can only be properly verified by obtaining measurements of arsenic in the field. These principles have already successfully helped to identify records of pollution in Cameroon, Italy, Laos and Uruguay. What can be done is to compare the predicted areas with the known occurrences. In this respect, mapping from North America, Europe and Australasia is most important because these are the areas where arsenic is most likely to have been most completely mapped to date. Hence, these areas are discussed before the continents where the risks of unrecognised arsenic pollution may be greater.

The objective of the main model is to predict arsenic in alluvial aquifers, which as noted earlier, is of pre-eminent importance in terms of human exposure. Hence, failure to predict occurrences in bedrock does not reflect on the main model. It is important, however, to examine its ability to correctly identify the worst affected areas, and the extent to which it over- or underestimates the size of the affected areas and exposed populations. The models, of course, do not predict whether the population are actually exposed to arsenic – only whether they would be if they consume untreated groundwater, or use this water for irrigation. Technically, the model predicts hazard. This assessment of health risk requires using other information to determine whether there will be either present or future exposure.

It should be appreciated that there are variable uncertainties related to knowledge of processes and the geology of the different regions, which are discussed where appropriate below. When examining the individual continental comparisons (Figures 3 to 8) it is helpful to also consider the distributions of population at risk shown in Figures 10 and 11, which emphasise the importance of the individual hazards.

4.2 Europe, North America and Australasia

Europe. There are only two major occurrences of alluvial arsenic pollution in Europe: the Po Basin in northern Italy, and the inland part of the Danube bounded by the Carpathian Mountains in Hungary, Croatia and western Romania. These are both well predicted by the model, although the known distribution is patchier than predicted, and has not been reported from Serbia[2] as predicted by the model. Both are mobilised by reductive dissolution, as predicted.

The model also predicts pollution along the Lower Danube, which is consistent general water quality information from Bucharest (Zamfirescu et al, 1999). There are minor reports of low-level arsenic in the Rhine alluvium, and in alluvial deposits of the Tiber in Italy (Vivona et al., 2004), but as regards the predictions along the upper Garonne and Saone in France, the Ebro and Xuquer in Spain, the Vistula in Poland, the Dniester in the Ukraine, and in southern Russia, there is no evidence of presence or absence of arsenic.

The general absence of alluvial arsenic in northern and western Europe reflects the absence of young mountains with suitable source rocks and high sediment loads.

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[2] Since writing this, a report of arsenic pollution in Serbia has been obtained (Habuda-Stanic et al., 2007), but it has not yet been discovered whether this is in alluvium.

USA and Canada. Arsenic pollution occurs over large areas of North America, although often in either glacial or bedrock aquifers, while non-glacial alluvial aquifers are only contaminated in the west. Consistent with this limitation, the model only predicts arsenic pollution along, and adjacent to, the Rockies, and correctly predicts polluted groundwater in the Rio Grande Basin and the Carson Desert in the southwest, the Willamette Basin of Oregon, the Snake River in Idaho, the Platte River in Idaho and at Fairbanks and the Kennai Peninsula in Alaska. That more of the rivers in the Basin and Range province in southwest USA is related to the complex mapping of Quaternary deposits there. However, the San Joaquin valley of California was identified after inclusion of the ‘proluvium’ (see discussion of Nepal below). Also, the absence of reports of arsenic in many of the basins flowing northeast from the Rockies in Canada and Alaska is readily explained by the low population density and probable use of surface water sources. The general absence of arsenic pollution in the alluvial basins of the eastern half of the USA and Canada strongly supports the formulation of the model.

Australasia. The near absence of reported alluvial arsenic pollution in Australia is consistent with the model predictions. So, on the other hand, is the widespread occurrence of contaminated groundwater in the North Island of New Zealand, although the model also predicts pollution in South Island, but this has not been reported. The reported cases, as predicted, are associated with reductive dissolution or geothermal activity. The model predicts arsenic pollution in the eastern islands of Papua New Guinea (see also below), from where no relevant information has been obtained.

4.3 Asia

The predicted extent of pollution is more extensive than has been reported, although the largest of the unconfirmed areas are in the sparsely populated and poorly documented (at least in English) northeast of Russia (Siberia). The worst affected areas are all accurately predicted, not only the continuous belt along the Indo-Gangetic and Brahmaputra plains, but also the Mekong, Red and Irrawaddy river plains. The known As-polluted areas in Japan and Taiwan are also predicted. The near omission of Nepal was identified as a flaw in the initial model due to the exclusion of proluvial alluvium ([Type=37]), although the situation in Nepal is complicated by the precision of mapping at the boundary between the Terai and the Himalayan front. Including this mapping unit had a large impact on the at-risk population in Asia, though much less so elsewhere in the world.

In China, the polluted middle sections of the Yellow (Huang He) River are predicted by the model, but so also are the lower reaches, from where arsenic has not been reported. It is believed that the absence of pollution in the lower reaches is substantially correct, and is attributed to the massive gain in suspended silt from the eastern side of the Loess Plateau. The model also predicts the occurrence of arsenic along the middle reaches of the Yangtze River, which has not been confirmed, and is one of the more notable ‘gaps’ in the present mapping of arsenic. The Yangtze and Lower Yellow rivers also have massive populations, and have major implications for the at-risk population in China (see Section 4.7).

Two densely populated areas are predicted to be at risk of having contaminated groundwater and where there are no, or very few, reports of pollution. The first is in the Tigris-Euphrates basin in Iraq, and the second are the multiple alluvial basins in the volcanic islands of Indonesia, Malaysia, the Philippines and Papua New Guinea.

4.4 South and Central America

In South America, the volcanic-loessal alluvial aquifers of Argentina are moderately well predicted, although it is unclear whether the differences are due to the model or to incomplete mapping of either arsenic or the Pampean Loess. The influence of geothermal sources on surface water, and to a lesser extent groundwater, is recognised in northern Chile and Bolivia. No other major occurrences of arsenic are known from South America, however, the model predicts large areas where groundwater may also be contaminated. The first group are basins in the semi-arid south of Argentina (south of the Bahia Blanco), where the alluvium may contain significant quantities of volcanic material, and where arsenic might be mobilised by alkali-desorption. The second group are some of the upper tributaries of the Amazon and Orinoco that fill foreland basins on the western flanks of the Andes.

In Central America, there is undoubtedly extensive arsenic pollution in Mexico, although the mechanisms and detailed distribution are poorly documented. There are also indications of pollution elsewhere in the Isthmus of Panama, but it is unclear how serious this is. The model also indicates multiple occurrences of As-contaminated groundwater throughout the region, including the larger Caribbean islands such as Cuba and Hispaniola.

4.5 Africa

Based on current knowledge, Africa is the least affected continent. Moreover, of the known cases, only two are in alluvial aquifers, and only one of these, a small occurrence in the volcanic region of southwest Cameroon was predicted by the model. The apparent rarity of arsenic in Africa may be confirmed by subsequent testing and, if so, is probably due its prolonged tectonic stability and tropical weathering regime. Of the Tertiary mountain chains, only the Atlas Mountains conform to the types of destructive plate boundaries associated with arsenic elsewhere.

The largest areas with predicted arsenic-risk occur around the Rift Valley, Ethiopian highlands and Ruwenzoris. Although a weak link to arsenic has been established in the Ethiopian section of the Rift Valley (Reimann et al., 2003), it is unclear whether these volcanoes, associated plutons and uplifted rocks represent a major source of sediment carrying available-arsenic. Similar uncertainties surround sediment derived from the mountains of South Africa. Indeed, the mountains of Southern Africa might well have been excluded, but were included by application of the precautionary principle

4.6 The Sulphide-Oxidation Model

National predictions from the sulphide-oxidation are included in Table 5. Known cases of sulphide-oxidation and some occurrences where the mechanism was not established, but SO was suspected, coincide with model predictions in Burkina Faso, Ghana, Sweden, parts of Mexico, and two cases in the USA. However, there are so many predicted cases where As-pollution has not been identified, that the predictive value of the model must be questioned. The global distribution of sulphide-oxidation risk is shown in Figure 9, however, less significance is given the output of the SO model in developing recommendations for further investigation.

Notwithstanding the reservations expressed above, a few interesting observations may be made. The top ten countries, in terms of population at risk, were also predicted (and known) to have high risks of As-pollution in alluvium. The most at-risk countries were indicated to be China and India, though perhaps a simple reflection of their size and population. The third and fourth countries on the list were the Philippines and Malaysia, which also had the highest at-risk populations for alluvial-arsenic amongst countries where significant pollution has not been reported, and tends to confirm the suggestion that there is a high risk of arsenic pollution in these countries. Among the countries where no alluvial-arsenic risk was identified, the highest (SO risk) ranking countries were Ghana, Kazakhstan and Burkina Faso, of which the two African countries are both known to contain significant arsenic pollution that has been attributed sulphide oxidation of gold bearing Birimian rocks.

4.7 Secondary Data Processing

The most notable changes to the model, during development, were (i) the inclusion of 'proluvial' alluvium ([Type]=37) based largely on the failure to predict As-pollution on the Nepal Terai, and (ii) the exclusion of all deposits pre-dating the Upper Quaternary where reductive-dissolution was the predicted mechanism.

Two predicted regions of high risk, the lower Chao Praya delta (in Thailand) and the Yellow River (in China) below where the Great Bend turns to the south, were excluded because these were known, with reasonable certainty, to be unaffected.

It is considered that a lower degree of confidence should be applied to predictions areas where there is particular scientific uncertainty (e.g. the influence of volcanic activity along the East African Rift Valley) or where there are particular geological reasons for doubting the occurrence of arsenic pollution.

4.8 Summary and Screening by Country

Globally, a risk of pollution is predicted in 107 countries, of which arsenic contamination was the known to occur in 54 countries, leaving 53 countries where a risk of arsenic is predicted and from where no relevant evidence to confirm or refute this has been found. However, in a few of the predicted and known occurrences, arsenic was not drawn from alluvial aquifers. In sixteen countries, arsenic pollution has been observed but was not predicted by the alluvial model, but only in four was arsenic reported from alluvial aquifers. Of these, two came from the Rhine delta which is not very surprising in that pollution was predicted in the upper reaches of the Rhine. The occurrence from Uruguay is also unsurprising as it represents a subsurface continuation (not shown in the ESRI database) of the Pampean loess that causes extensive pollution in Argentina. Only the pollution at Perth in Western Australia (Appleyard et al., 2006) and the low-level contamination in the Okavango delta of Botswana[3] (Huntsman-Mapila et al., 2006) were completely outside the bounds of the model. In addition, since Draft Report of this study was submitted, reports, but no details, have come to light of the presence of arsenic in Serbia and Montenegro (Habuda-Stanić et al., 2007), and also of natural arsenic contamination in the southwest of South Korea (Ahn, 2004), all of which are consistent with model predictions.

In Europe, North America and Australasia, most known cases of As-contaminated were simulated by the GIS model. In Asia, all the most severely affected areas are predicted, while the most important gaps in

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[3] Botswana is predicted to be affected, but not this area.

knowledge, where arsenic might be found are in the Yangtze and Tigris-Euphrates basins and along the Indonesian arc. In South America, As-pollution in Argentina and Chile were simulated, but a much larger areas of pollution are predicted along the western fringes of the Andes. In Africa, there is a poor relation between the known and predicted distribution of arsenic in groundwater, and uncertainty about the importance of mountains in Eastern and Southern Africa as sources of As-rich sediment.

The countries and populations at risk of being exposed to arsenic pollution in alluvial groundwater are listed in Table 4, and the distribution of population at risk shown in Figures 10 and 11. It is repeated that these population figures are not exposure estimates, only populations of the regions within which an arsenic pollution risk is judged to apply. Given the immediate objective of identifying areas where there is an unrecognised arsenic risk, the countries have been classified and grouped according to the following criteria:

1) As-status known; no pre-emptive action recommended because survey / mitigation in process
2) As-status unknown; clear scientific basis for action
3) As-status unknown; questionable scientific basis for action
4) Some knowledge of As; extent seriously incomplete or grossly inadequate level of survey, so additional support is recommended
5) Some knowledge of As or presence is probable; small central American and Caribbean countries with little or no knowledge of As, for which coordinated action can be planned
6) Population at risk so small as to be considered very low priority
7) Appropriate action unclear

5 How to Interpret and Use Models Results

The first point to remember is that the population estimates quoted in Tables 4 to 7 are the populations of the areas where there is a significant risk that groundwater contains hazardous concentrations of arsenic. As discussed in section 2.3, these are not estimates of the exposed populations.

5.1 Initial Enquiries

Where a country or region, not presently recognised to have an arsenic problem, is predicted to have a risk of arsenic pollution, various steps can usefully be taken before beginning arsenic testing **in each specific region**. These include the following checks:

(i) Is groundwater use important in the identified region and, if so, are alluvial aquifers used?

(ii) Is alluvial groundwater drawn from dug wells, drilled wells, or both? This is important because arsenic distribution is often strongly correlated with well depth

(iii) Check with water supply and water resource agencies and research organisations to find out if they have tested for the presence of arsenic in previous investigations. While previous detections of high As-concentrations would have probably attracted attention, determinations of absence may not. Such organisations might also be useful sources of advice, and should be interested in any survey results.

(iv) Is alluvial groundwater also used for irrigation? If so, a second health risk, via the food chain, may be present.

(v) Public health officials and dermatologists should be consulted, and shown pictures of the milder forms of hyper- and hypo-pigmentation and keratosis, to find out whether they suspect having seen such symptoms before.

(vi) Discussions with fluvial geomorphologists or hydrologists may suggest whether the sediments are favourable for arsenic mobilisation by either the AD or RD mechanisms. Aside from any arsenic determinations that might be available, if the suspended sediment contains less than about 80% quartz or if the river water contains less than about 10% of silica, the chances of arsenic pollution in underlying alluvial groundwater will be higher. If possible, information on the quartz:feldspar:rock ratio (QFR) of the sediment should be collected.

5.2 If Reductive Dissolution is the Predicted Mechanism

Where reductive dissolution is suspected, simple information pointing to a higher or low risk of pollution can easily be obtained from in-house knowledge, local literature or talking to water professionals. There are two preconditions for reductive-dissolution: first a source of suitable sediment in which arsenic adsorbed to iron oxides, and second a strongly reducing depositional environment. The types of information to be looked for include:

(i) The highest As-concentrations can be expected in drilled wells within a few tens of metres of the surface. Dug wells are likely to have low As-concentrations, as are wells deeper than 50 to 150 metres. Arsenic may be present but not at the depths currently exploited, and therefore a latent problem.

(ii) Wells with high arsenic concentrations nearly always have high iron concentrations. However, many wells with high iron concentrations do not have high arsenic concentrations.

(iii) Reports of black peaty layers or the presence of buried vegetation during well drilling should be considered a risk factor for arsenic. Associated reports of methane (sometimes burning) discharges are also an indicator of the strongly reducing conditions that favour reductive-dissolution.

(iv) Pollution is more likely where the water table fluctuates within a few metres of the surface. Very deep (tens of metres or more) water levels will tend to reduce the risk of arsenic pollution.

Pollution by reductive dissolution is rare in bedrock aquifers other than at the contact with polluted alluvial deposits.

5.3 If Alkali-Desorption is the Predicted Mechanism

Though less widespread, prediction of AD-type arsenic is more problematic, but the following points should be considered:

(i) pH ≥8.0, and especially pH ≥8.5, is a major risk factor.

(ii) Interbedding of alluvial aquifers with Quaternary volcanic sediments such as ash, tuff or loess that is rich in volcanic glass (as in Argentina) should also be considered major risk factors.

(iii) Although AD-type waters are mostly oxic, they have been reported from subsiding basins in arid parts of China, where arsenic is accompanied by very high concentrations of organic acids.

(iv) No simple relation between As-concentrations and the depth of wells should be expected.

(v) Many AD-type groundwaters also contain toxic concentrations of fluoride, and hence, within the regions predicted by the model, the one can be considered a risk factor for the other. This should be investigated when consulting relevant agencies and designing sampling programmes.

Pollution by alkali-desorption also occurs in bedrock aquifers, but is more difficult to predict, and may require specialist advice.

5.4 Surveys of Arsenic in Well Waters

If, after considering the above, it is judged that field surveys are required, the local WES section should take advice from UNICEF staff who have conducted such surveys in other countries. Planning of such surveys should include the following points:

(i) Testing will probably use a combination of field test-kits and laboratory testing. Since local laboratories will not have a track-record in arsenic testing, either two local laboratories or one local and one international laboratory should be used.

(ii) Sampling should be structured to represent the range of well depths and geological or geomorphological conditions in the area. Basic details of well construction, history and water use should be recorded. The treatment or storage of water prior to use could reduce As-concentrations, while the use of water in cooking could increase exposure.

(iii) Measuring other aspects of water quality, especially parameters such as pH and iron concentration are very useful, but for an initial survey, must be decided on the basis of local conditions. Nevertheless, any notable features of taste, colour, smell or the visible presence of gases should always be recorded.

6 Predictions of Arsenic Risk by Region

In the predictions that follow, attention focuses on the Developing World, with a general bias towards countries where the predicted population at risk is highest and scientific confidence is greatest. Examples are also chosen to represent conditions in Asia, South America and Africa that may act as models other countries with smaller predicted populations at risk. In each country description, reasons are presented to have confidence in, and/or to question, the significance of the predictions. It is hoped that, through the experience gained, these reasons will help to refine the search for other affected aquifers.

6.1 Europe, North America and Australasia

In relation to the objectives of this study, and the relatively high-level of existing knowledge, no detailed predictions are offered here for these regions. The main areas of risk that are not known to have been investigated are Vistua and San basins in southeast Poland, the lower Danube in Romanian and Bulgaria, and the Manych, Terek and Kuban basins in southern Russia.

6.2 Asia

Indonesia. The distribution of arsenic-pollution risk in the Indonesian archipelago is shown in Figure 12a, while Figure 12b and Table 6 show the distribution of population at-risk, which total 13.8M at risk from alluvial arsenic and a further 1.7M at risk from sulphide-oxidation. Due to the humid climate, the risk stems dominantly from reductive-dissolution, but geothermal activity is common throughout the islands. The most extensive risk areas occur on the islands of Kalimantan, Irian Jaya and along the north coast of Sumatra. However, due to the distribution of population, the greatest concentrations of population at-risk are in Java, and in small areas near Padang in Sumatra and near Bandjarmasin in Kalimantan.

There are several reasons to think there may be extensive pollution in Indonesia. Unpublished data from UNICEF indicates the presence of arsenic in wells in the Aceh Province in the northwest of Sumatra, and Sriwana et al. (1998) reported As-rich hot springs discharging into rivers in Java. Although there are no other groundwater arsenic data, alluvial groundwater from densely populated areas in the north of Java (IWACO, 1994) is strongly reducing, with high concentrations of iron, manganese, bicarbonate and ammonium, and discharges of methane gas. In addition, extensive, low-lying areas in the north of Sumatra and the south of Kalimantan are underlain by thick beds of peat which could provide the necessary redox driver to drive reductive-dissolution. Further evidence of the presence of arsenic comes from measurements in Java of 24 µg/L in river water and 7.5 mg/kg in the suspended load of the Solo River, and 19 µg/L in the Porong River (van der Sloot, 1989).

In so far as there are reasons to question extensive mobilisation of arsenic, the most important differences to the known affected areas of Asia lie in the upper catchments, which were not glaciated in the Pleistocene, and where chemical weathering is more intense than in the Himalayas. A possible consequence of this difference is that arsenic may be weathered and leached in the soil zone prior to erosion.

Iraq. The distribution of arsenic-pollution risk and the population at-risk in Iraq are shown in Figure 13. It is estimated that 4.2 million people live in the area of alluvial arsenic risk, plus 20,000 at risk from arsenic mobilised by sulphide-oxidation in one area of Kurdistan. Risk is widely distributed along the floodplains of the Tigris and Euphrates, with the greatest number of people at risk living along the Tigris south of Baghdad. Due to the dry climate, the model predicts that arsenic would be mobilised predominantly by alkali-desorption, however, superficial similarities with the Indus system and inland basins in China suggest that arsenic might in fact be mobilised by reductive-dissolution, a view that is supported by the widespread occurrence of interbedded peat (Baltzer and Purser, 1990). The QFR ratio of the sands (37:10:53) and the anionic composition of river water all suggest that the fluvial environment is favourable for arsenic mobilisation (Ravenscroft et al., 2008).

Philippines. The distribution of arsenic-pollution risk in the Philippines is shown in Figure 14a, while Figure 14b and Table 7 show the distribution of population at-risk, which total 2.7M at risk from alluvial arsenic and a further 1.9M at risk from sulphide-oxidation. The entire Philippines are formed of young volcanic mountains, but major alluvial deposits are formed only on the larger islands of Luzon and Mindanao. The island of Luzon lies directly to south of, across the Luzon Strait, and along the same tectonic island arc, as Taiwan, which is severely contaminated by arsenic. Consequently, under the prevailing humid climate, the alluvial risk comes from reductive-dissolution in these two islands only. Little information was available on water quality from alluvial aquifers other than noting high iron and manganese concentrations under reducing conditions (Fujita et al., 1990). However, high As-concentrations are well-known in geothermal waters, and on Mindanao, Webster (1999) found hot springs containing 4-6 mg/L As leaking into the Marbel and Matingao rivers which contained up to 140 and 260 μg/L respectively. The Philippines are intensely mineralised, and consequently a widespread risk of arsenic pollution by sulphide-oxidation is predicted, however, it is uncertain to what extent this may be converted into human exposure.

Uzbekistan. The distribution of arsenic-pollution risk and the population at-risk in Uzbekistan are shown in Figure 15. Both the alluvial arsenic risk, which is dominantly attributed to alkali-desorption risk (1.25M) with minor component attributed to reductive-dissolution (0.15M), are strongly concentrated along the plains of the Amudar'ya and its tributaries that drain into the Aral Sea. There is also a risk from sulphide-oxidation (0.3M) in the northeast. The geological conditions are rather different to the better documented affected regions, and no information was available on groundwater conditions in Uzbekistan, however, such information might exist in the Russian literature, which should be searched before further action is taken.

6.3 South and Central America

Colombia. The distribution of arsenic-pollution risk and the population at-risk in Colombia are shown in Figure 16. Colombia can be considered in two parts: a mountain belt in the northwest that runs along the coast, where the drainage is dominated by the Magdalena river; and uplands to the southeast that drain into the Orinoco or Amazon systems with few large alluvial basins except that between the Arauca and Meta channels (Figure 16a). The arsenic risk lies primarily in the northern intermontane basins, where arsenic may be mobilised by reductive-dissolution (1.48M) with lesser components of risk deriving from and by alkali-desorption (0.18M) in drier areas and from sulphide-oxidation (0.25M) in the intensely mineralised, volcanic terrain of the central mountains. Few relevant groundwater data are available, although alluvial groundwater in the Rio de Bogota basin is strongly reducing as indicated by methanogenesis resulting from degradation of peat (Castrillon et al., 2004). The composition of sediment and water from the Magdalena river are intermediate (Figure 2) between the main groups of As-affected and unaffected basins. The thick sequence of Holocene channel-fill and interbedded overbank muds (Smith, 1986) appear favourable to reductive-dissolution.

Venezuela. The distribution of arsenic-pollution risk and the population at-risk in Venezuela are shown in Figure 17. Areas at risk of pollution cover large areas of the Orinoco floodplains, although smaller areas on the northern coast underlie the main areas of population at risk. In terms of population, reductive-dissolution (0.69M) is the main threat, with a small risk from alkali-desorption (0.08M), but there are significant populations (0.27M) coincident with areas where there may be a risk from sulphide-oxidation. Although the model suggests an arsenic-risk in the Orinoco delta, sands of the Orinoco delta are chemically mature (QFR 93:01:06) and therefore generally unfavourable to arsenic mobilisation, and the risk is probably restricted to the northeastern tributaries that drain the northern Andes, where Johnsson et al. (1991) report much less mature sand compositions (of the order of QFR 45:45:10).

More information on groundwater in both Colombia and Venezuela should be available in the regional literature in Spanish.

6.4 Africa

Ethiopia. The distribution of arsenic-pollution risk and the population at-risk in Ethiopia are shown in Figure 18. Geologically, in the nature of their volcanism and mountain building, the East African Rift and Ethiopian Highlands differ fundamentally from all other arsenic-affected regions, and so any analogies should be treated with caution. Nevertheless, there have been detections of arsenic (up to 90 µg/L) during reconnaissance geochemical surveys (Reimann et al., 2003), however, arsenic and other water quality issues in groundwater were over-shadowed by the high levels of fluoride encountered. Consequently, little attention was given to arsenic, and this remains a serious gap in knowledge. Rainfall varies greatly in Ethiopia, and as a consequence widespread risks of arsenic pollution are predicted due to both alkali-desorption risk (1.78M) and reductive-dissolution (1.74M). The population at risk are concentrated along the central rift valley. In addition, the model indicates a significant population (0.69M) at risk from pollution due to sulphide-oxidation in the northwest of the country, but again, because of the different geological character of the region, these predictions should be treated with equal caution.

Sudan. The distribution of arsenic-pollution risk and the population at-risk in Sudan are shown in Figure 19. Alluvial arsenic risk is widely distributed along the floodplains of the Nile and its tributaries, and is dominantly attributed to alkali-desorption (4.4M). However, it questionable whether the Jebel Mara volcanic region is sufficient to justify the risk assigned to the Bahr el Arab tributary. In the eastern tributaries that drain the Ethiopian highlands, the validity of the risk is conceptually the same as that discussed in relation to Ethiopia. In terms of population, there are minimal contributions to the predicted risk from either reductive-dissolution (12,000) or sulphide-oxidation (24,000). However, some caution is called for here, because arsenic might have been mobilised by reductive-dissolution during wetter phases of the Quaternary, so the relevant indicators (Section 5.2) should be looked for. No arsenic data are available, but Farah et al. (1997) report limited water quality data from the Gezira Formation near the Blue and White Nile near Khartoum where pH >8.0 is common.

Morocco. The distribution of arsenic-pollution risk and the population at-risk in Morocco are shown in Figure 20. The Atlas Mountains are at the western extremity of the Alpine-Himalayan chain. In the dry climate of Morocco, the risk in alluvial deposits is predominantly due to alkali-desorption (2.47M). Older sedimentary aquifers are also important in parts of northern Morocco and may reduce dependency on alluvial aquifers. A risk of pollution from sulphide-oxidation (0.39M) is widely distributed across the country.

7 Conclusions and Recommendations

Natural arsenic pollution is a global phenomenon, the known extent of which has increased rapidly in recent years, and is almost certainly incompletely mapped. In terms of human impact, the risk of arsenic pollution is located predominantly in young alluvial basins adjacent to active mountain belts, where mobilisation occurs by reductive-dissolution in humid climates and organic-rich environments, and by alkali-desorption in arid climates. A conceptually sound GIS model has been developed which successfully simulates most known occurrences in alluvial aquifers, and is judged suitable for predicting other locations where arsenic may be found. Active mountain belts are also the most common location for finding geothermal arsenic.

Arsenic pollution in bedrock aquifers is complex, albeit of lesser significance, and is less amenable to prediction from global data sets. Although a model has been developed to identify areas where, based on a presumed spatial association with economic sulphide mineralisation, arsenic mobilisation by sulphide-oxidation is relatively likely, less confidence is given to the outputs of this model.

In most cases, though with the notable exception of Bangladesh, the populations of the regions at risk are much higher than the known affected populations. This is not surprising, because in the affected alluvial areas, typically of the order of 20-50% of wells are contaminated, and similar proportions should be assumed to apply in the at-risk areas. In addition, many of the predicted regions have much lower population densities than in say the affected river basins of South and Southeast Asia, and consequently are likely to still be heavily dependent on surface water, such that percentages of 20-50% represent hypothetical future exposure patterns. And, if arsenic is present, such exposure is entirely avoidable.

In the case of sulphide-oxidation in bedrock aquifers, lower use of groundwater is to be expected because such aquifers are usually lower yielding, more difficult and more expensive to develop, and therefore less likely to exploited by, for example, the rural poor. Consequently, the ratio of at-risk to either the present or future exposed population is likely to be significantly lower than for alluvial aquifers.

Considering the outputs of the model in the light of the state of existing knowledge, and the particular geological setting and institution capacity of each country, a range of actions is recommended, as outlined in **Table 8**. It should be appreciated that subsequent discovery or non-discovery of arsenic in the countries identified will have implications that will increase or decrease the likelihood of finding arsenic in neighbouring countries with similar geology. For example:

1) Discovery of arsenic in Indonesia or the Philippines would make discovery in Malaysia and Papua New Guinea probable.
2) Discovery of arsenic in Colombia or Venezuela would make discovery in Peru, Ecuador and Brazil probable.
3) Discovery of arsenic in Ethiopia or the Sudan would make discovery in Kenya, Tanzania, Eritrea and Congo (DR) more probable.
4) Discovery of arsenic in Morocco would make discovery in Algeria probable.

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TABLES

Table 1. Combined Rainfall and Temperature Classes

Climate Class	**Rain Class**	**Temp Class**	**Criterion**	**Significance**	**Favoured Process**
0	0	All	<500 mm	Dry	AD
1	1	2	500-1000 and T > 10ºC	Semi-arid	AD
2	1	<2	500-1000 and T < 10ºC	Sub-humid	RD (low)
3	2	All	1000-1500	Sub-humid	RD (low)
4	3	All	> 1500	Humid	RD (high)

Table 2. Climatic and Geological Factors Favouring Arsenic Mobilisation

Climate Class	**Favoured Process**	**Alluvial Basin**	**Draining Tertiary mountains or volcano**	**Within mountains or 50 km from volcano**	**As Risk Class**
0	AD	Yes	Yes	No Yes	AD(H) AD(H) & GT
1	AD	Yes	Yes	No Yes	AD(L) AD(L) & GT
2	RD (low)	Yes	Yes	No Yes	RD(L) RD(L) & GT
3	RD (low)	Yes	Yes	No Yes	RD(L) RD(L) & GT
4	RD (high)	Yes	Yes	No Yes	RD(H) RD(H) & GT

Table 3. Model Classification of Population Density

GIS Code	GIS Legend (persons km^{-2})	Pop. Density Assigned (km^{-2})
0	Unpopulated	0
1	<1	0.5
2	1-10	5
3	10-25	17
4	25-50	38
5	50-100	75
6	100-200	150
7	200-400	300
8	400-800	600
9	> 800	1200

Modified after ESRI (1996)

Table 4. Countries Predicted to have a Risk of Arsenic Pollution in Alluvial Groundwater

Group	Country	Population at risk (1)	% of pop'l'n	Present As-Status (2)	Sources of uncertainty	Action	Comments
1	*As-status known; no specific pre-emptive action recommended because survey or mitigation in process*						
1	India	102,585,389	11%	Major		S/M	At-risk total exaggerated by narrow affected zones in Ganga & Brahmaputra plains, yet mapping incomplete
1	China	31,385,545	2%	Major		S/M	Mapping incomplete. Status of Yangtze basin uncertain
1	Bangladesh	30,969,023	26%	Major		S/M	Actual exposure greater, mapping complete
1	Pakistan	23,202,777	18%	Major		S/M	Mapping incomplete
1	Vietnam	15,603,743	22%	Major		S/M	
1	United States	6,225,436	2%	Major		S/M	Well investigated
1	Italy	5,210,010	9%	Major		S/M	Well investigated
1	Mexico	5,041,626	5%	Major		S/M	
1	Japan	4,910,456	4%	Major		S/M	
1	Taiwan	4,133,413	19%	Major		S/M	
1	Argentina	2,551,845	8%	Major		S/M	
1	Cambodia	2,422,367	27%	Major		S/M	
1	Nepal	1,465,928	7%	Major		S/M	
1	Hungary	1,422,290	14%	Major		S/M	
1	Canada	1,404,935	5%	Significant reports		S/M	
1	Chile	1,046,749	8%	Significant reports		S/M	More testing of groundwater advised
1	Afghanistan	984,444	6%	Significant reports		S/M	Only partial mapping possible due to security issues
1	Croatia	898,534	18%	Significant reports		S/M	
1	Romania	837,825	4%	Isolated reports		TR	
1	Germany	762,714	0.9%	Significant reports		S/M	
1	Poland	625,557	2%	Isolated reports		U	
1	France	569,565	1.0%	Significant reports		S/M	
1	Spain	432,152	1.1%	Significant reports		S/M	
1	New Zealand	313,091	9%	Significant reports		S/M	
1	Bosnia & Herzegovina	247,715	9%	Isolated reports		U	
1	Slovakia	244,292	5%	Significant reports		LS	
1	Austria	207,033	3%	No information		U	
1	Greece	69,253	0.7%	Significant reports		S/M	
1	Slovenia	45,398	2%	Isolated reports		LS	

Group	Country	Population at risk (1)	% of pop'l'n	Present As-Status (2)	Sources of uncertainty	Action	Comments
2	*As-status unknown; clear scientific basis for action*						
2	Indonesia	13,782,332	7%	Isolated reports	Insufficient testing	TR	Reports from Aceh require confirmation
2	Iraq	4,245,527	20%	No information		TR	
2	Philippines	2,680,901	4%	Geothermal-As		TR	
2	Morocco	2,468,982	9%	No information		TR	
2	Colombia	1,664,092	5%	No information		TR	
2	Uzbekistan	1,399,980	7%	No information		LS	
2	Malaysia	1,370,416	7%	Isolated reports		TR	
2	Turkmenistan	1,202,084	32%	No information		LS	
2	Ukraine	841,619	2%	No information		LS	
2	Venezuela	763,253	4%	No information		TR	
2	Algeria	689,857	3%	No information		TR	
2	Papua New Guinea	458,860	11%	No information		TR	
2	Syria	436,887	3%	No information		TR	
2	Tajikistan	396,892	7%	No information		TR	
2	Tunisia	343,316	4%	No information		TR	
2	Paraguay	117,134	2%	No information		TR	Possible extension of Pampean loess
2	Saudi Arabia	84,502	0.5%	Isolated reports		TR	
2	North Korea	75,856	0.3%	No information		TR	
2	Libya	50,782	1.0%	No information		TR	
2	South Korea	39,472	0.1%	No information		LS	
2	Yemen	32,105	0.2%	No information		TR	
2	Albania	31,548	0.9%	No information		U	
2	Montenegro	10,191	1.6%	No information		LS	

Group	Country	Population at risk (1)	% of pop'l'n	Present As-Status (2)	Sources of uncertainty	Action	Comments
3	*As-status unknown; questionable scientific basis for action*						
3	Sudan	4,395,759	16%	No information	Nature of source rocks	TR	Uncertainty stems from lack of comparable area
3	Ethiopia	3,528,594	7%	Isolated reports	Nature of source rocks and volcanic activity	TR	High level of uncertainty due to lack of comparable
3	South Africa	2,689,641	7%	No information	Nature of source rocks	U	Mountain ranges different to other areas
3	Tanzania, Utd Rep.	1,917,411	7%	No information	Nature of source rocks and volcanic activity	TR	Uncertainty stems from lack of comparable area
3	Zaire	1,308,690	3%	No information	Nature of source rocks and volcanic activity	TR	Uncertainty stems from lack of comparable area
3	Kenya	1,185,834	5%	No information	Nature of source rocks and volcanic activity	TR	Uncertainty stems from lack of comparable area
3	Somalia	800,437	8%	No information	Nature of source rocks	TR	Uncertainty stems from lack of comparable area
3	Mozambique	497,169	3%	No information	Nature of source rocks	U	Mountain ranges different to other areas
3	Rwanda	255,307	3%	No information	Nature of source rocks and volcanic activity	TR	Uncertainty stems from lack of comparable area
3	Burundi	172,923	3%	No information	Nature of source rocks	U	Uncertainty stems from lack of comparable area
3	Jordan	146,488	4%	No information		T	
3	Uganda	139,863	0.8%	Isolated reports	Nature of source rocks	U	Uncertainty stems from lack of comparable area
3	Israel	90,133	2%	No information		U	
3	West Bank	66,560	5%	No information		TR	
3	Lesotho	64,089	3%	No information	Nature of source rocks	U	Mountain ranges different to other areas
3	Zimbabwe	39,954	0.4%	No information	Nature of source rocks	U	Mountain ranges different to other areas
3	Malawi	28,929	0.3%	No information	Nature of source rocks and volcanic activity	TR	Uncertainty stems from lack of comparable area
3	Chad	27,380	0.4%	No information		TR	
3	Botswana	24,840	1.7%	Isolated reports	Nature of source rocks	U	Known from Okavango delta, but not predicted
3	Madagascar	22,529	0.2%	No information	Nature of source rocks	U	Uncertainty stems from lack of comparable area
3	Eritrea	20,837	0.6%	No information	Nature of source rocks and volcanic activity	TR	Uncertainty stems from lack of comparable area

Group	Country	Population at risk (1)	% of pop'l'n	Present As-Status (2)	Sources of uncertainty	Action	Comments
4	*Some knowledge of As; extent seriously incomplete or grossly inadequate level of survey, so additional support is recommended*						
4	Myanmar (Burma)	8,980,700	21%	Possibly major		TR	Probably severe, little mapping done
4	Thailand	5,239,326	9%	Isolated reports	Holocene sediments of Chao Phraya delta	U	
4	Russia	4,054,549	3%	Isolated reports		LS	Reports from deep bedrock and mineral waters only
4	Turkey	1,999,649	3%	Isolated reports		TR	Complex geological setting
4	Laos	1,500,011	32%	Isolated reports		U	
4	Iran	1,457,769	2%	Isolated reports		TR	Complex geological setting
4	Peru	1,229,749	5%	Isolated reports		TR	
4	Bolivia	737,713	10%	Significant reports		TR	Known on Altiplano, but not lowlands
4	Ecuador	572,832	5%	Isolated reports		TR	
4	Nigeria	90,813	0.1%	Isolated reports	Contradictory surveys	TR	Reports require confirmation
4	Cameroon	23,013	0.2%	Isolated reports		TR	
4	Mongolia	11,581	0.5%	Significant reports		S/M	Nature of affected aquifers unknown - possibly

Group	Country	Population at risk (1)	% of pop'l'n	Present As-Status (2)	Sources of uncertainty	Action	Comments
5	*Some knowledge of As or presence is probable; small central American and Caribbean countries with little or no knowledge of As, for which coordinated action can be planned*						
5	Nicaragua	212,096	5%	Significant reports		TR	
5	Guatemala	207,541	2%	No information		TR	
5	Panama	189,437	7%	No information		TR	
5	Dominican Republic	126,880	2%	No information		TR	
5	Haiti	100,979	1.4%	No information		TR	
5	Costa Rica	97,507	3%	Isolated reports		TR	
5	Cuba	91,110	0.8%	Isolated reports		TR	
5	El Salvador	69,285	1.2%	Significant reports		TR	
5	Belize	45,181	22%	No information		TR	
5	Honduras	7,523	0.1%	Isolated reports			

Group	Country	Population at risk (1)	% of pop'l'n	Present As-Status (2)	Sources of uncertainty	Action	Comments
6	*Population at risk so small as to be considered very low priority*						
7	*Appropriate action unclear*						
6	Djibouti	8,486	1.9%	No information			
6	Bhutan	4,776	0.3%	No information		TR	
6	Kuwait	3,177	0.2%	No information			
6	Brunei	2,169	0.8%	No information			
6	Solomon Islands	924		No information			
6	Zambia	288	0.003%	No information			
6	Azerbaijan	273	0.005%	No information			Has major arsenic mine
6	San Marino	252	1.1%	No information			
6	Kyrgyzstan	196	0.004%	No information			
6	Czech Republic	129	0.001%	Reported in bedrock			
6	Armenia	100	0.003%	No information			
7	Serbia	976,929	10%	No information		LS	
7	Brazil	262,584	0.2%	Isolated reports		TR	
7	Bulgaria	184,802	2%	No information		LS	
	Total	**324,919,389**					

Notes:

1 The 'at-risk' population refers the population of the potentially affected area, and not to the exposed population (see section 2.3)

2 Refers only to alluvial aquifers

TR	Basic testing required as soon as possible
S/M	Survey and/or mitigation programmes ongoing
U	Uncertain, requires discussion
LS	Literature survey in appropriate language as first step

Group codes

1 As-status known; no specific pre-emptive action recommended because survey / mitigation in process
2 As-status unknown; clear scientific basis for action
3 As-status unknown; questionable scientific basis for action
4 Some knowledge of As; extent seriously incomplete or grossly inadequate level of survey, so additional support is recommended
5 Some knowledge of As or presence is probable; small central American and Caribbean countries with little or no knowledge of As, for which coordinated action can be planned
6 Population at risk so small as to be considered very low priority
7 Appropriate action unclear

Table 5. Populations At-Risk from Arsenic Pollution from Alluvial Sources and Sulphide-Oxidatic

Country	Population at risk (Alluvial: AD & RD)	Population at risk (Sulphie oxidation)	Combined Population at risk	Major Source
India	102,585,389	2,632,895	105,218,284	All.
China	31,385,545	14,973,719	46,359,264	All.
Bangladesh	30,969,023	0	30,969,023	All.
Pakistan	23,202,777	2,806	23,205,583	All.
Vietnam	15,603,743	911,741	16,515,484	All.
Indonesia	13,782,332	1,710,273	15,492,605	All.
Myanmar (Burma)	8,980,700	360,342	9,341,042	All.
United States	6,225,436	742,659	6,968,095	All.
Japan	4,910,456	827,048	5,737,504	All.
Thailand	5,239,326	437,798	5,677,124	All.
Mexico	5,041,626	626,141	5,667,767	All.
Russia	4,054,549	1,508,971	5,563,520	All.
Italy	5,210,010	0	5,210,010	All.
Taiwan	4,133,413	1,009,713	5,143,126	All.
Philippines	2,680,901	1,900,513	4,581,414	All.
Sudan	4,395,759	23,619	4,419,378	All.
Iraq	4,245,527	19,793	4,265,320	All.
Ethiopia	3,528,594	693,571	4,222,165	All.
South Africa	2,689,641	798,346	3,487,987	All.
Morocco	2,468,982	393,994	2,862,976	All.
Argentina	2,551,845	125,853	2,677,698	All.
Cambodia	2,422,367	88,528	2,510,895	All.
Turkey	1,999,649	459,899	2,459,548	All.
Tanzania, United	1,917,411	221,176	2,138,587	All.
Peru	1,229,749	887,029	2,116,778	All.
Malaysia	1,370,416	723,583	2,093,999	All.
Zaire	1,308,690	638,242	1,946,932	All.
Colombia	1,664,092	254,533	1,918,625	All.
Nepal	1,465,928	283,997	1,749,925	All.
Uzbekistan	1,399,980	295,151	1,695,131	All.
Iran	1,457,769	232,268	1,690,037	All.
Canada	1,404,935	202,237	1,607,172	All.
Laos	1,500,011	75,051	1,575,062	All.
North Korea	75,856	1,449,788	1,525,644	**SO**
Hungary	1,422,290	101,716	1,524,006	All.
Kenya	1,185,834	236,990	1,422,824	All.
Germany	762,714	632,509	1,395,223	All.
Algeria	689,857	682,595	1,372,452	All.
Nigeria	90,813	1,228,405	1,319,218	**SO**
Poland	625,557	582,434	1,207,991	All.
Turkmenistan	1,202,084	0	1,202,084	All.
Chile	1,046,749	136,186	1,182,935	All.
Serbia	976,929	186,648	1,163,577	All.
Romania	837,825	294,436	1,132,261	All.
Afghanistan	984,444	96,767	1,081,211	All.
Venezuela	763,253	274,990	1,038,243	All.
Ukraine	841,619	165,429	1,007,048	All.
Bolivia	737,713	231,789	969,502	All.
Ecuador	572,832	382,351	955,183	All.
Croatia	898,534	0	898,534	All.
France	569,565	325,850	895,415	All.
Spain	432,152	442,415	874,567	**SO**
Somalia	800,437	15,201	815,638	All.
Ghana	0	810,108	810,108	**SO**
Tunisia	343,316	365,059	708,375	**SO**
Kazakhstan	0	625,829	625,829	**SO**
South Korea	39,472	534,144	573,616	**SO**
Brazil	262,584	309,307	571,891	**SO**

Table 5. Populations At-Risk from Arsenic Pollution from Alluvial Sources and Sulphide-Oxidatic

Country	Population at risk (Alluvial: AD & RD)	Population at risk (Sulphie oxidation)	Combined Population at risk	Major Source
Mozambique	497,169	64,954	562,123	All.
Tajikistan	396,892	108,673	505,565	All.
Papua New Guinea	458,860	29,837	488,697	All.
Cuba	91,110	391,998	483,108	**SO**
Eritrea	20,837	437,286	458,123	**SO**
Syria	436,887	0	436,887	All.
Burundi	172,923	240,509	413,432	**SO**
Zimbabwe	39,954	373,309	413,263	**SO**
Slovakia	244,292	151,570	395,862	All.
Bulgaria	184,802	169,164	353,966	All.
Burkina Faso	0	352,237	352,237	**SO**
Kyrgyzstan	196	346,470	346,666	**SO**
Rwanda	255,307	63,053	318,360	All.
New Zealand	313,091	0	313,091	All.
Czech Republic	129	306,000	306,129	**SO**
Zambia	288	305,159	305,447	**SO**
Austria	207,033	74,751	281,784	All.
Nicaragua	212,096	56,382	268,478	All.
Bosnia and Herzegovir	247,715	10,062	257,777	All.
Panama	189,437	56,428	245,865	All.
Dominican Republic	126,880	101,658	228,538	All.
Guatemala	207,541	0	207,541	All.
Angola	0	181,812	181,812	**SO**
Georgia	0	181,216	181,216	**SO**
Madagascar	22,529	149,103	171,632	**SO**
Uganda	139,863	30,314	170,177	All.
Armenia	100	160,870	160,970	**SO**
Costa Rica	97,507	61,839	159,346	All.
Jordan	146,488	12,525	159,013	All.
Niger	0	143,627	143,627	**SO**
Ireland	0	129,406	129,406	**SO**
Azerbaijan	273	128,664	128,937	**SO**
Finland	0	122,375	122,375	**SO**
Paraguay	117,134	0	117,134	All.
Greece	69,253	42,069	111,322	All.
Saudi Arabia	84,502	25,032	109,534	All.
Honduras	7,523	98,719	106,242	**SO**
Puerto Rico	0	103,842	103,842	**SO**
Haiti	100,979	0	100,979	All.
Botswana	24,840	74,900	99,740	**SO**
Central African	0	93,662	93,662	**SO**
Australia	0	91,792	91,792	**SO**
Israel	90,133	783	90,916	All.
Namibia	0	78,712	78,712	**SO**
Yemen	32,105	45,260	77,365	**SO**
Togo	0	76,296	76,296	**SO**
El Salvador	69,285	0	69,285	All.
Slovenia	45,398	22,851	68,249	All.
West Bank	66,560	0	66,560	All.
Lesotho	64,089	0	64,089	All.
United Kingdom	0	62,537	62,537	**SO**
Sierra Leone	0	62,366	62,366	**SO**
Ivory Coast	0	56,447	56,447	**SO**
Sweden	0	53,929	53,929	**SO**
Cameroon	23,013	29,842	52,855	**SO**
Benin	0	52,672	52,672	**SO**
Libya	50,782	0	50,782	All.
Belize	45,181	0	45,181	All.

Table 5. Populations At-Risk from Arsenic Pollution from Alluvial Sources and Sulphide-Oxidatic

Country	Population at risk (Alluvial: AD & RD)	Population at risk (Sulphie oxidation)	Combined Population at risk	Major Source
Mongolia	11,581	32,298	43,879	**SO**
Norway	0	40,207	40,207	**SO**
Congo	0	37,764	37,764	**SO**
Guinea	0	32,545	32,545	**SO**
Fiji	0	32,179	32,179	**SO**
Albania	31,548	0	31,548	All.
Portugal	0	31,166	31,166	**SO**
Liberia	0	31,056	31,056	**SO**
Malawi	28,929	0	28,929	All.
Chad	27,380	0	27,380	All.
Macedonia	0	24,255	24,255	**SO**
Cyprus	0	21,790	21,790	**SO**
Gabon	0	19,029	19,029	**SO**
Mauritania	0	14,799	14,799	**SO**
Egypt	0	11,934	11,934	**SO**
Senegal	0	11,094	11,094	**SO**
Mali	0	10,739	10,739	**SO**
Montenegro	10,191	0	10,191	All.
New Caledonia	0	9,205	9,205	**SO**
Djibouti	8,486	0	8,486	All.
Guyana	0	7,379	7,379	**SO**
Bhutan	4,776	0	4,776	All.
Oman	0	3,990	3,990	**SO**
Kuwait	3,177	0	3,177	All.
French Guiana	0	2,292	2,292	**SO**
Brunei	2,169	0	2,169	All.
Belgium	0	1,349	1,349	**SO**
Solomon Islands	924	0	924	All.
Swaziland	0	805	805	**SO**
San Marino	252	0	252	All.
United Arab Emirates	0	182	182	**SO**
Greenland	0	0	0	**SO**
Total	**324,919,389**	**50,561,454**	**375,480,843**	

Notes:

1 The 'at-risk' population refers the population of the potentially affected area, and not to the exposed population (see section 2.3)

Table 6. At-Risk Population in Indonesia

Province	Population at risk (Alluvial)	Population at risk (sulphide-oxidation)	Total Population at Risk[1]
Java	9,870,011	1,159,394	11,029,405
Sumatra	2,476,531	88,414	2,564,945
Kalimantan	1,297,437	69,769	1,367,206
Sulawesi	-	295,116	295,116
Irian Jaya	138,312	877	139,189
Other islands	41	96,703	96,744
Total	13,782,332	1,710,273	15,492,605

1. See section 2.3 for explanation

Table 7. At-Risk Population in the Philippines

Island	Population at risk (Alluvial/RD)	Population at risk (sulphide-oxidation)	Total Population at Risk[1]
Bohol		1,000	1,000
Cebu		500,079	500,079
Luzon	2,484,703	842,203	3,326,906
Masbate		45,989	45,989
Mindanao	196,198	166,191	362,389
Negros		266,961	266,961
Other		4,651	4,651
Palawan		13,897	13,897
Samar		59,542	59,542
Total	**2,680,901**	**1,900,513**	**4,581,414**

1. See section 2.3 for explanation

Table 8. Recommended Strategies for Countries where an Arsenic Pollution Risk is Identified

Category	Recommended Action(s)	Relevant Examples	Comments
1 Arsenic pollution is well known, and a substantial mitigation programme is ongoing.	Share model output for consideration in ongoing activities.	India, China, Vietnam, Cambodia, Argentina, Chile, Mexico, Hungary, Croatia, Italy, Spain	Possible regional gaps in China and Mexico
2 No significant knowledge of arsenic pollution (or evidence of absence) and large population at risk (geological confidence high).	Provide technical support to research available knowledge with a view to planning and commissioning surveys.	Indonesia, Philippines, Malaysia, Papua New Guinea, Colombia, Venezuela, Paraguay, Haiti, Dominican Rep., Cuba, Costa Rica, North Korea, South Korea	First priority for action
3 No significant knowledge of arsenic pollution (or evidence of absence) and large population at risk (geological confidence moderate).	Share model output, plus technical support aimed at better researching available knowledge	Iraq, Uzbekistan, Turkmenistan, Ukraine, Tajikistan, Morocco, Algeria, Libya, Tunisia, Syria, Saudi Arabia, Yemen	Second priority for action
4 Some knowledge of arsenic pollution, but apparently significantly incomplete mapping and large population at risk (geological confidence high).	Share model output, plus technical support, possibly through regional workshops[1].	Myanmar, Bolivia, Thailand, Nicaragua, El Salvador, Peru, Bolivia, Ecuador, Laos, Russia	Support likely to be needed on a regional basis
5 Some knowledge of arsenic pollution, but apparently significantly incomplete mapping and large population at risk (geological confidence moderate).	Share model output, plus technical support, possibly through regional workshops[1].	Iran, Turkey	
6 Some knowledge of arsenic pollution, but possibly incomplete mapping, but with relatively sophisticated scientific infrastructure.	Share model output with relevant water agencies.	Romania, Poland	
7 Existing knowledge adequate	No action required	Bangladesh, USA	

Notes: 1. Such workshops should include and other relevant chemical water quality issues

FIGURES

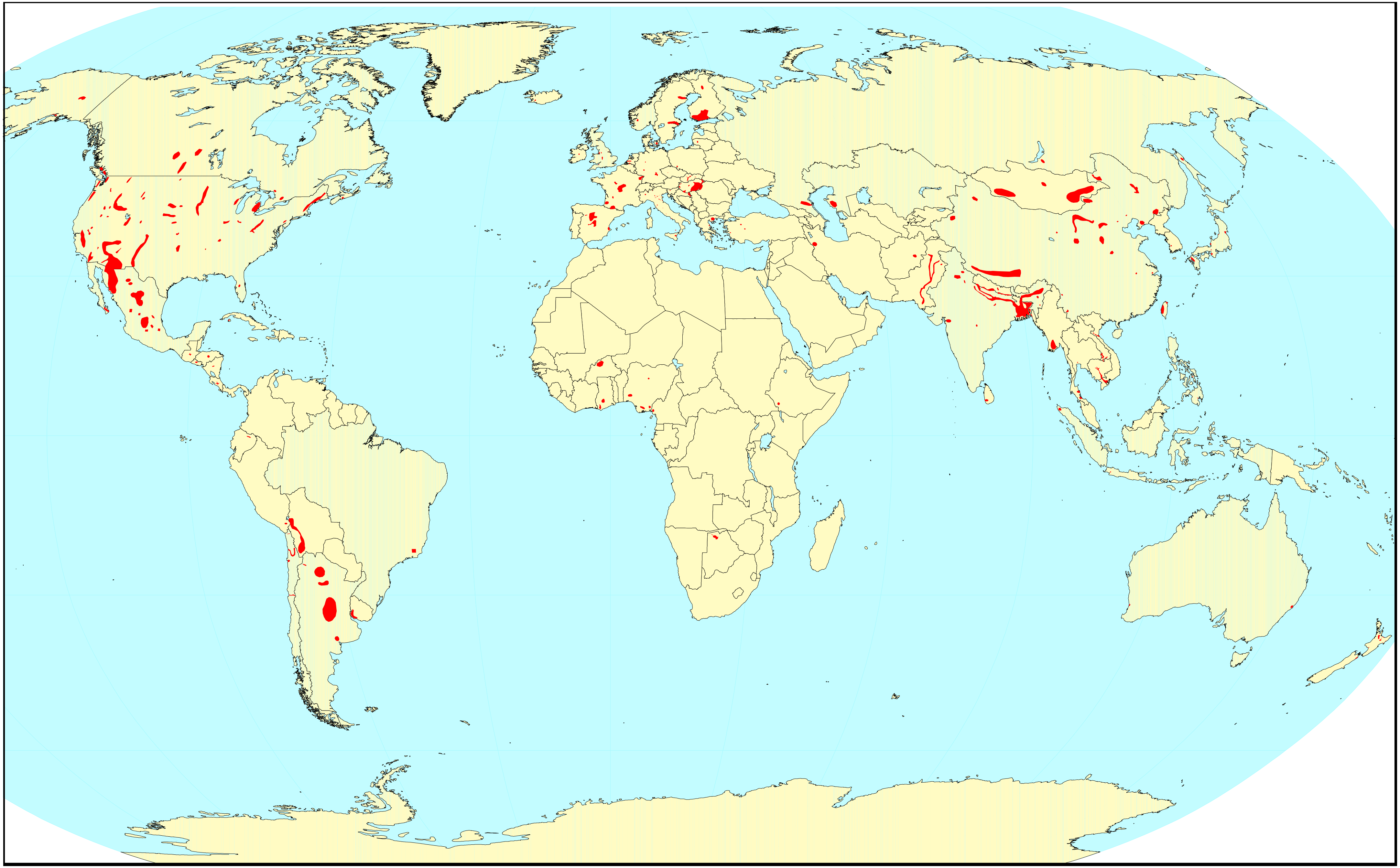


Fig. 1. Known Areas with Natual Arsenic Contamination

Notes: Data from Ravenscroft et al. (2008). See Appendix I for details.

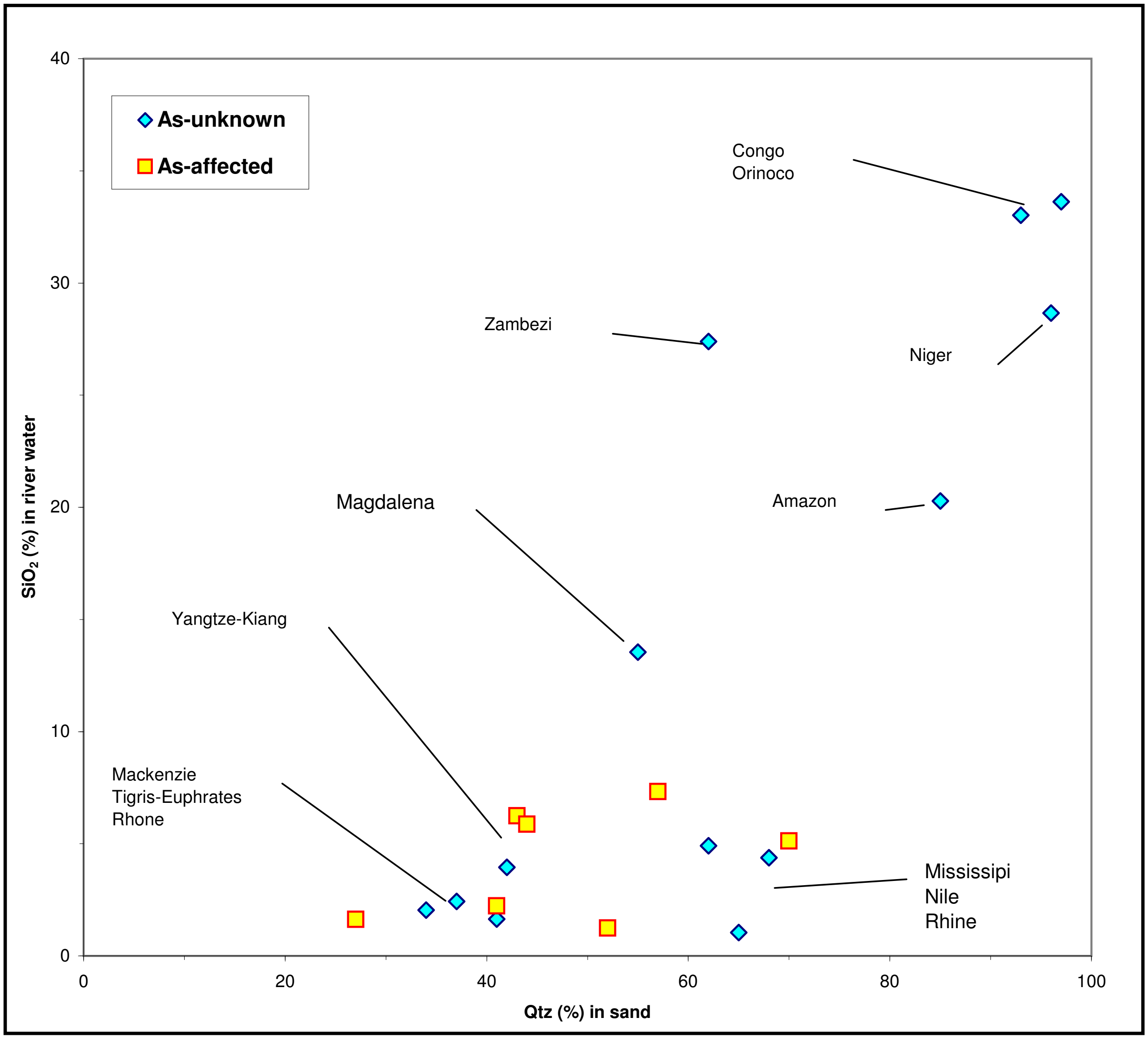


Fig. 2. Sediment and Water Chemistry in Arsenic Affected River Basins

Notes. Quartz as % of Quartz + feldspar + rock fragments in suspended sediment. SiO_2 as a % of SiO_2 + HCO_3 + (Cl+SO_4) in river water. The arsenic affected rivers are the Po, Danube, Ganges-Brahmaputra, Indus, Mekong, Yellow and Yukon.From data compilation by Ravenscroft et al. (2008).

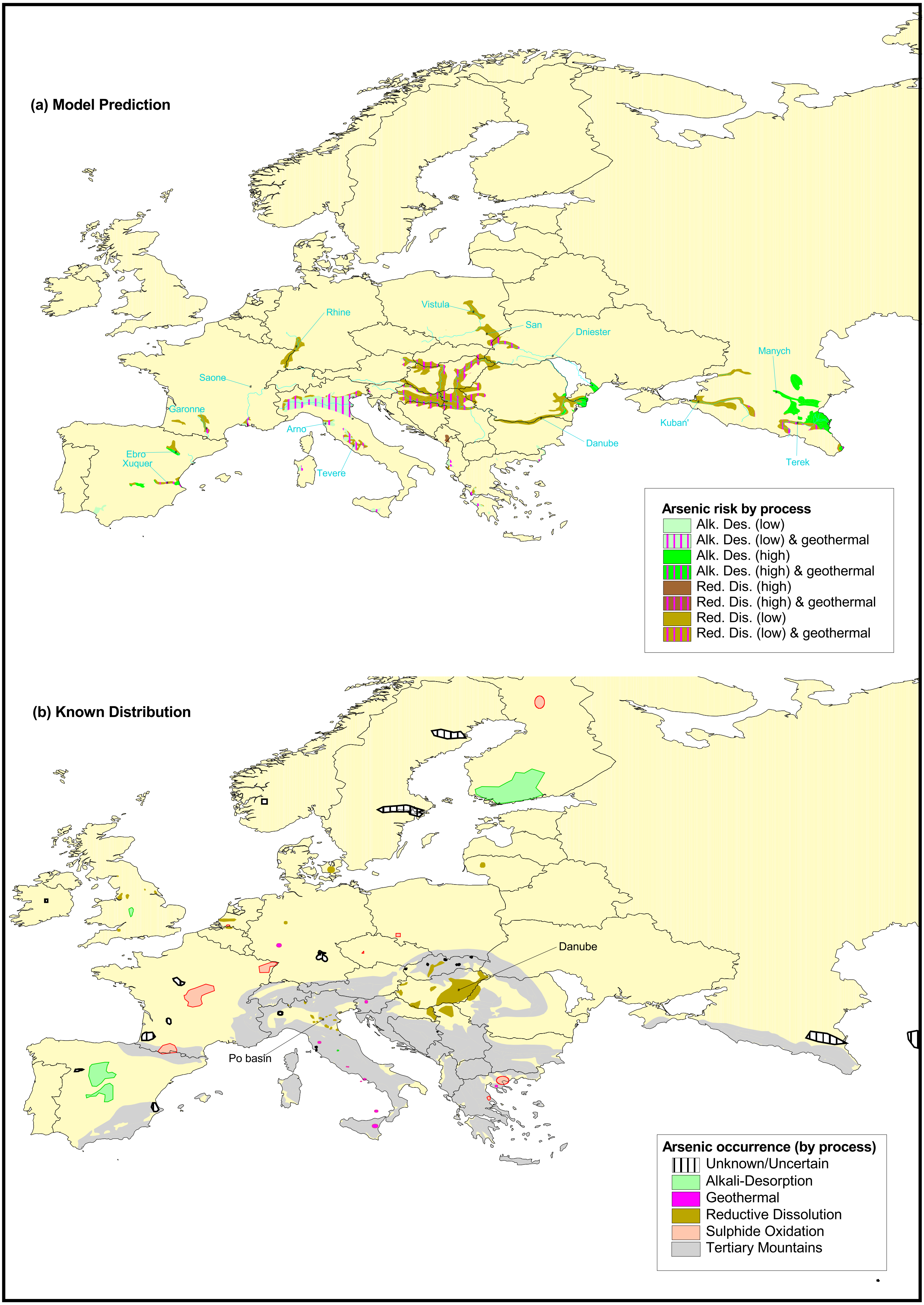
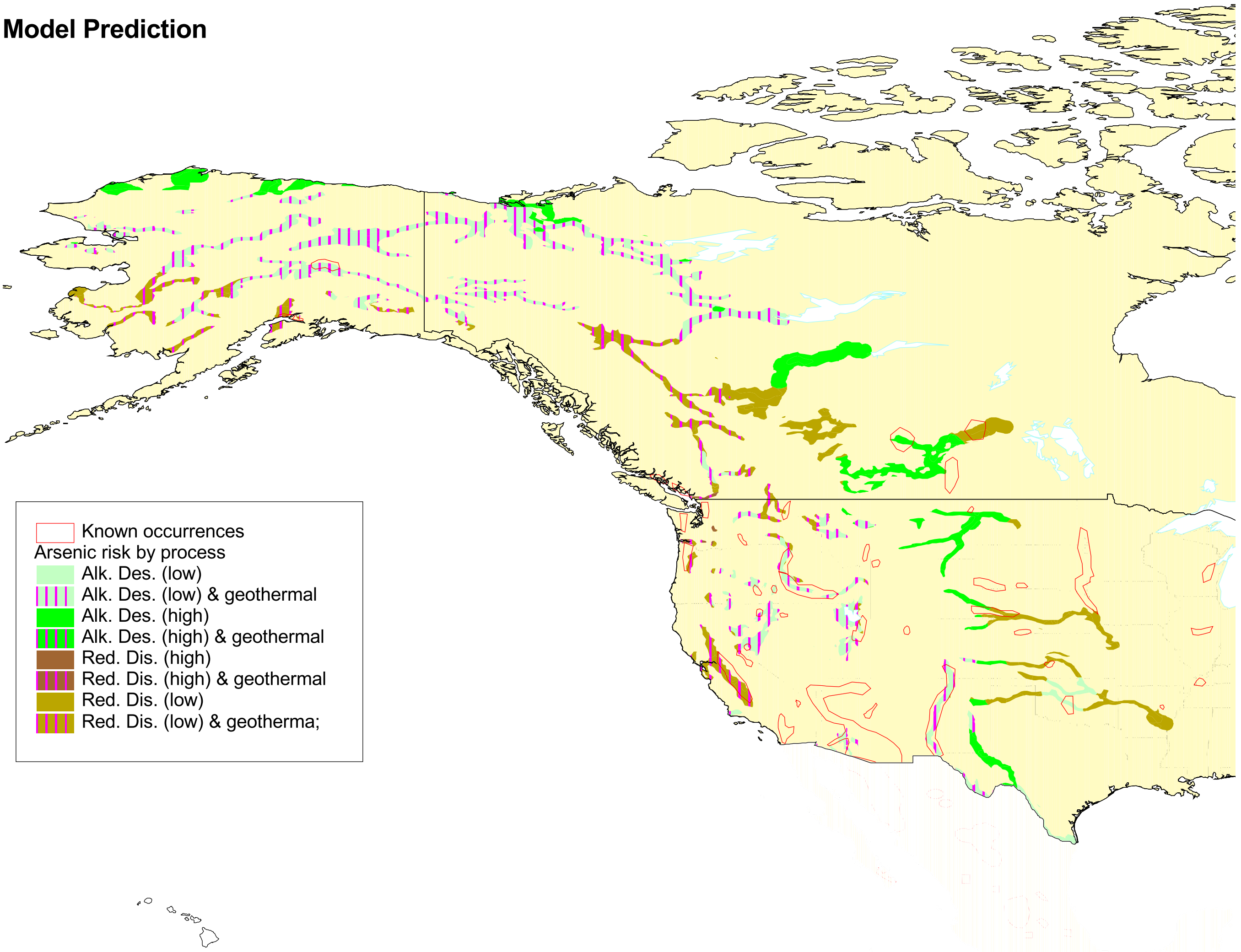


Fig. 3. Known and Predicted Distribution of Arsenic in Europe

(a) Model Prediction



(b) Known Distribution

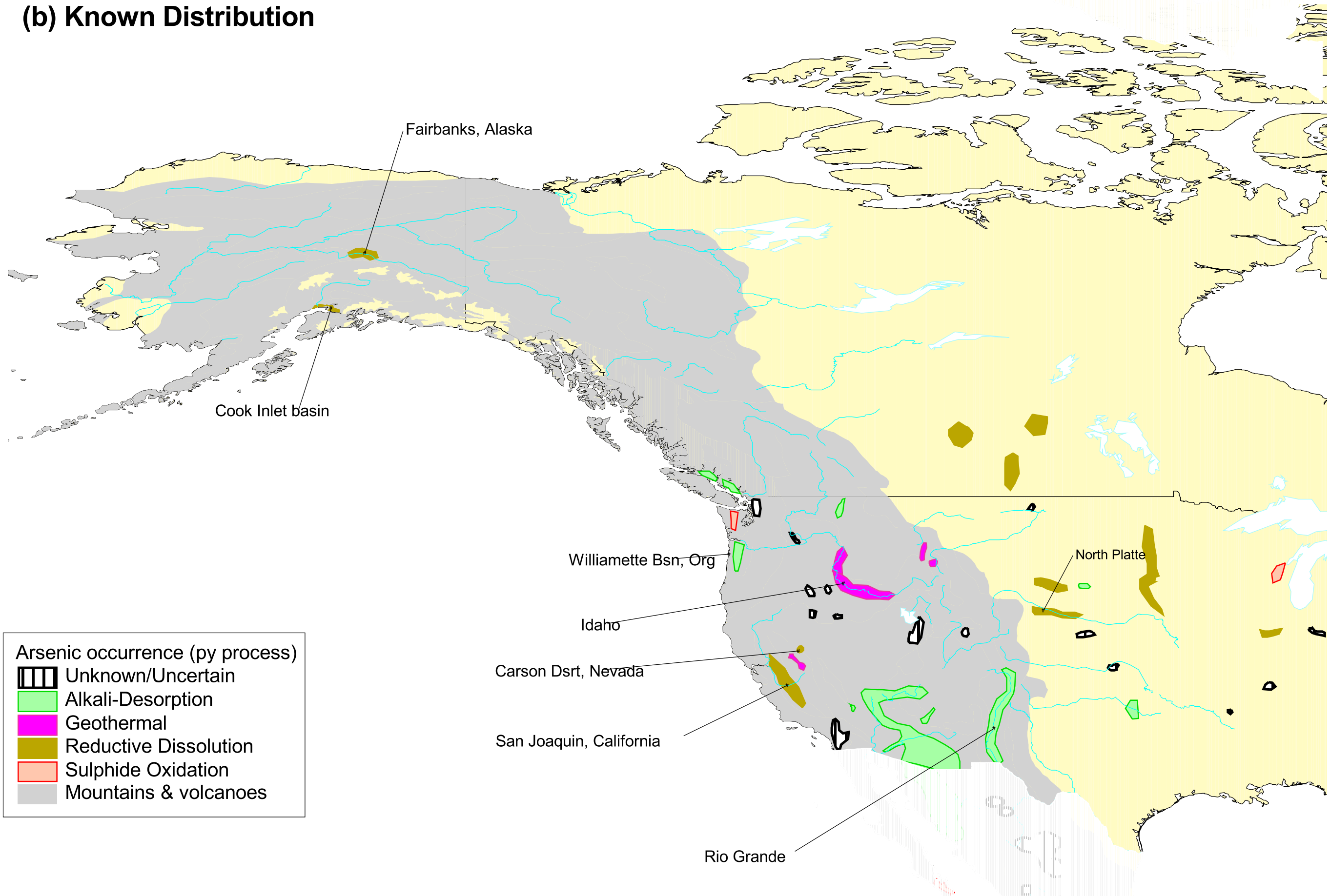
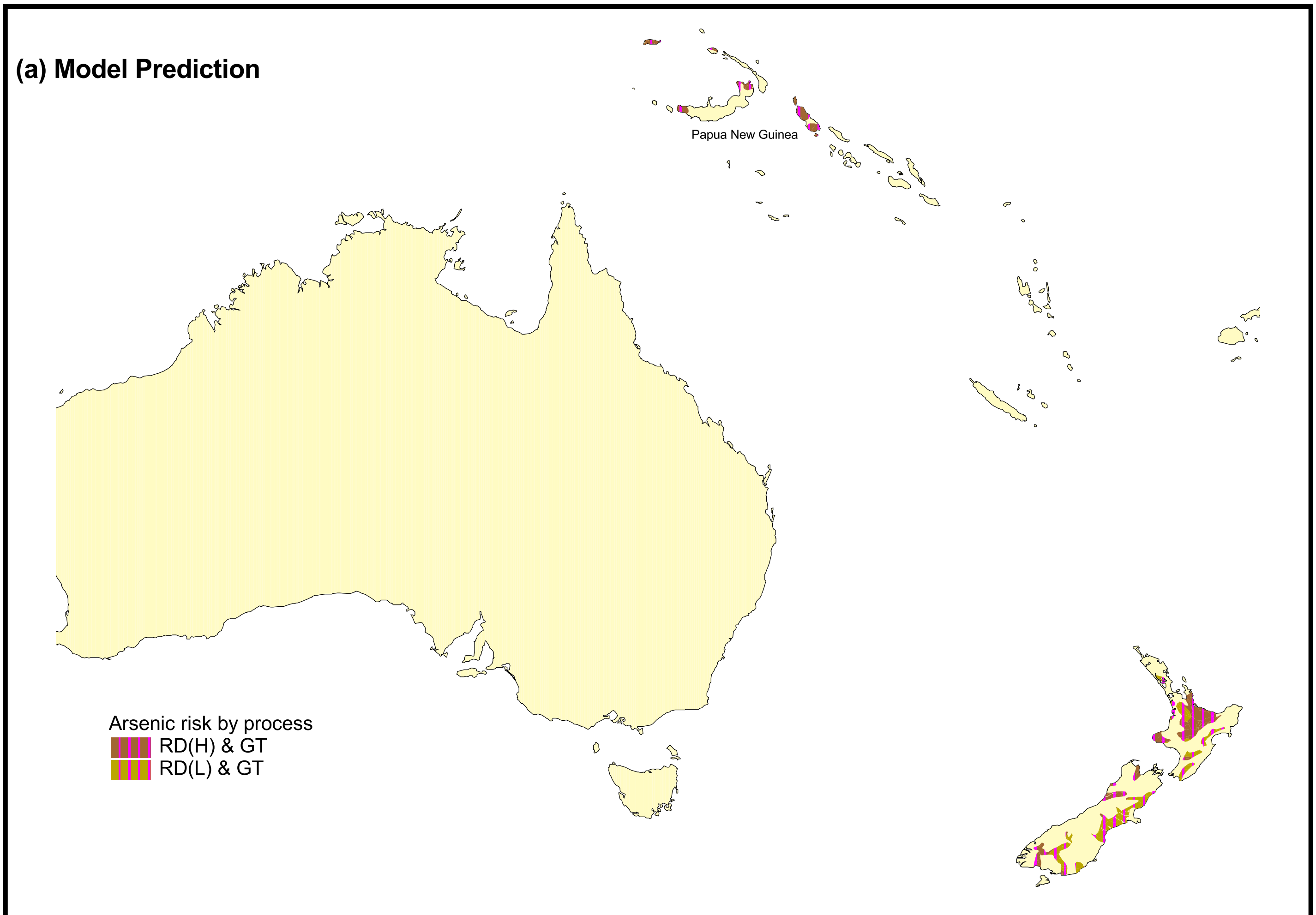


FIg. 4. Known and Predicted Distribution of Arsenic in USA and Canada

(a) Model Prediction



(b) Known Occurrences

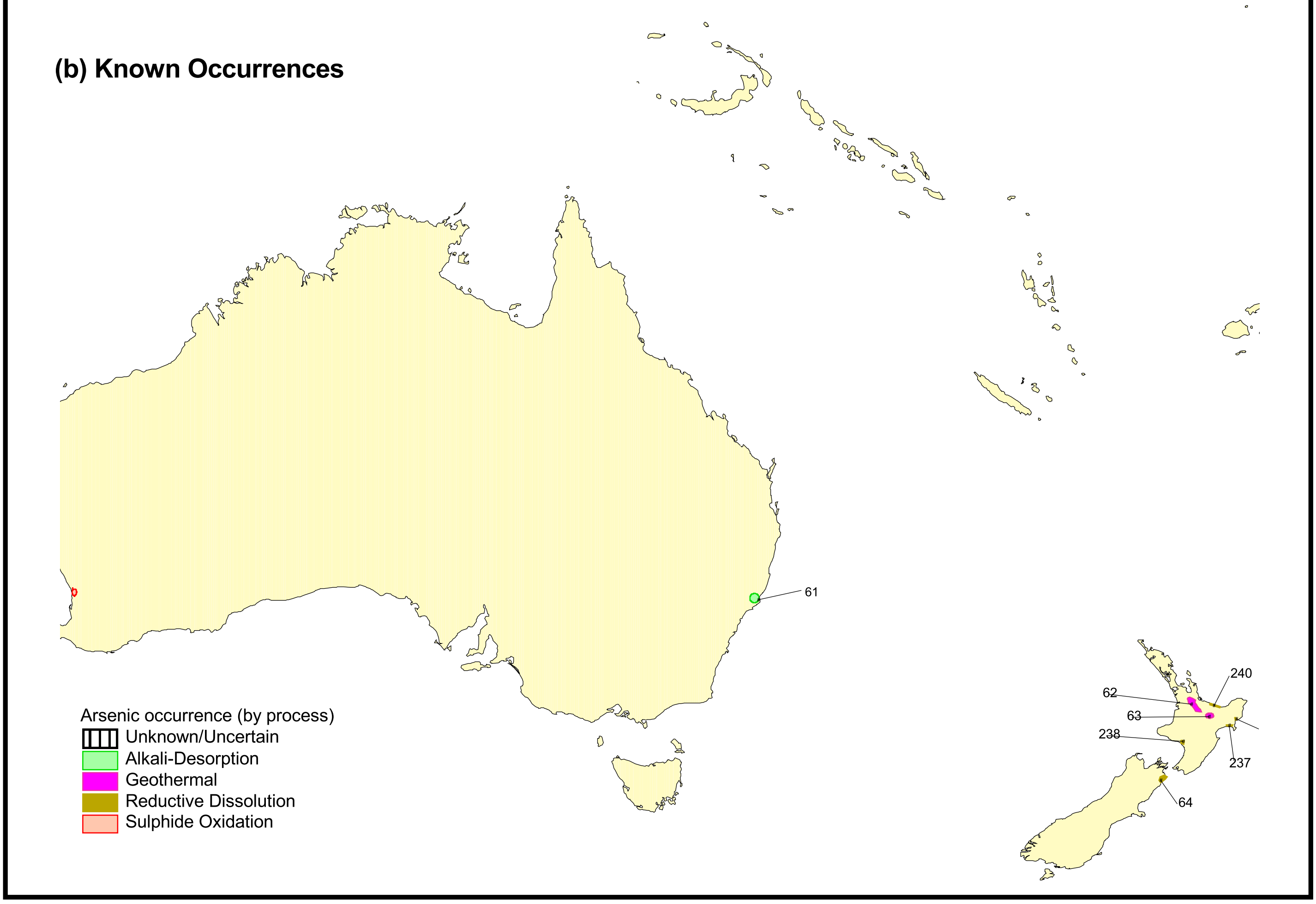
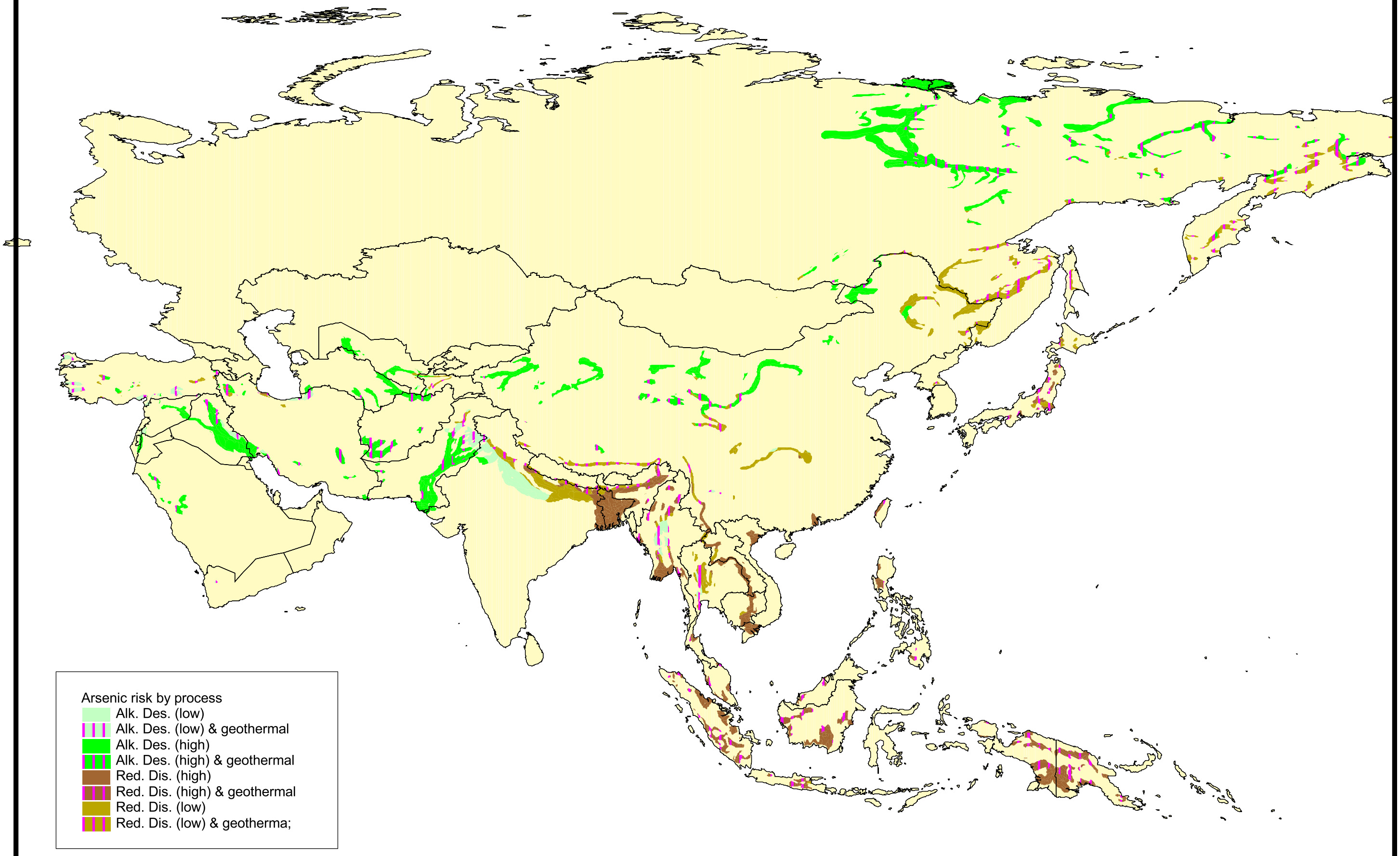


Fig. 5. Known and Predicted Distribution of Arsenic in Australasia

(a) Model Predictions



(b) Known Occurrences of Arsenic Pollution

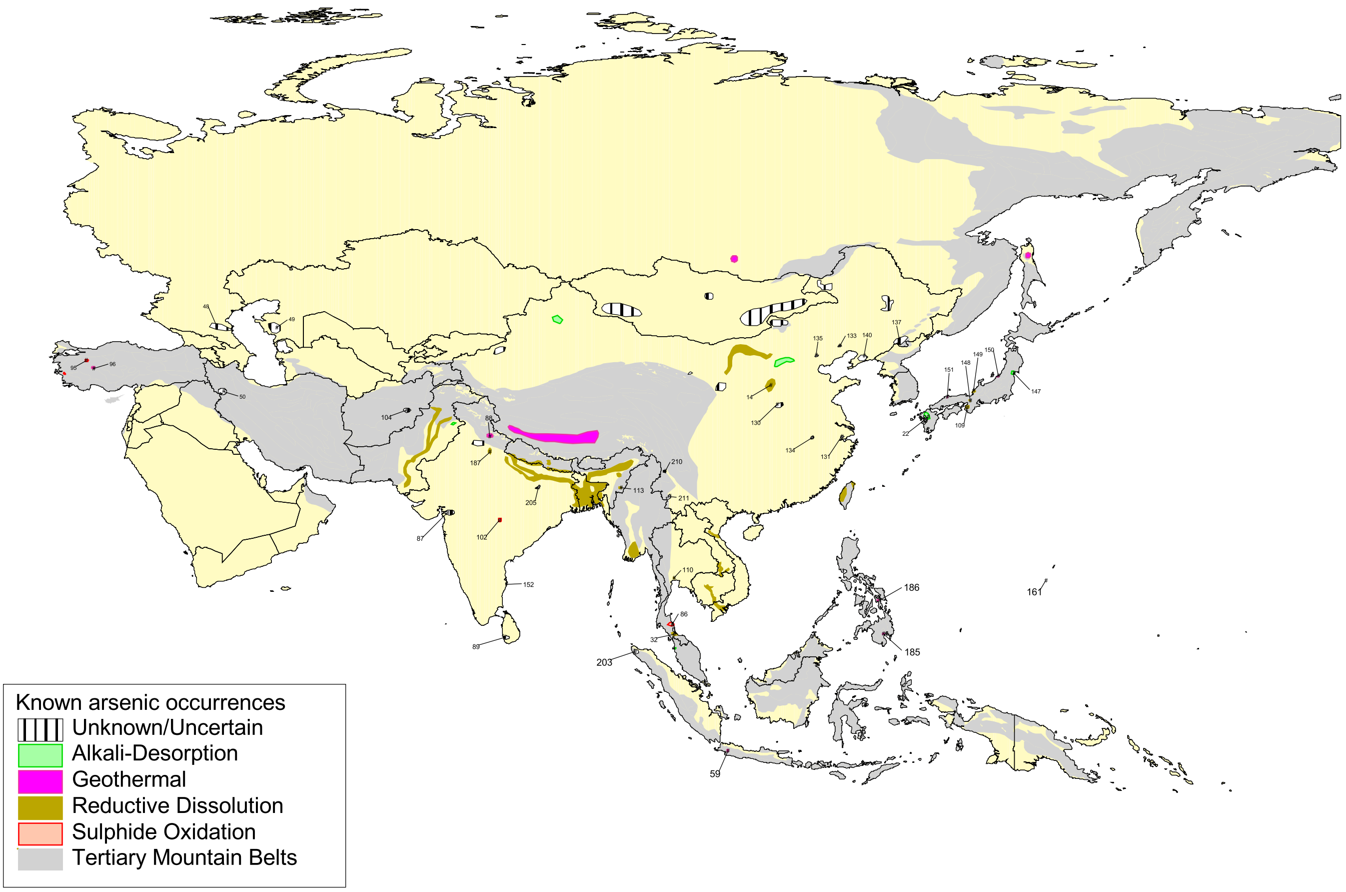


Fig. 6. Known and Predicted Distribution of Arsenic in Asia

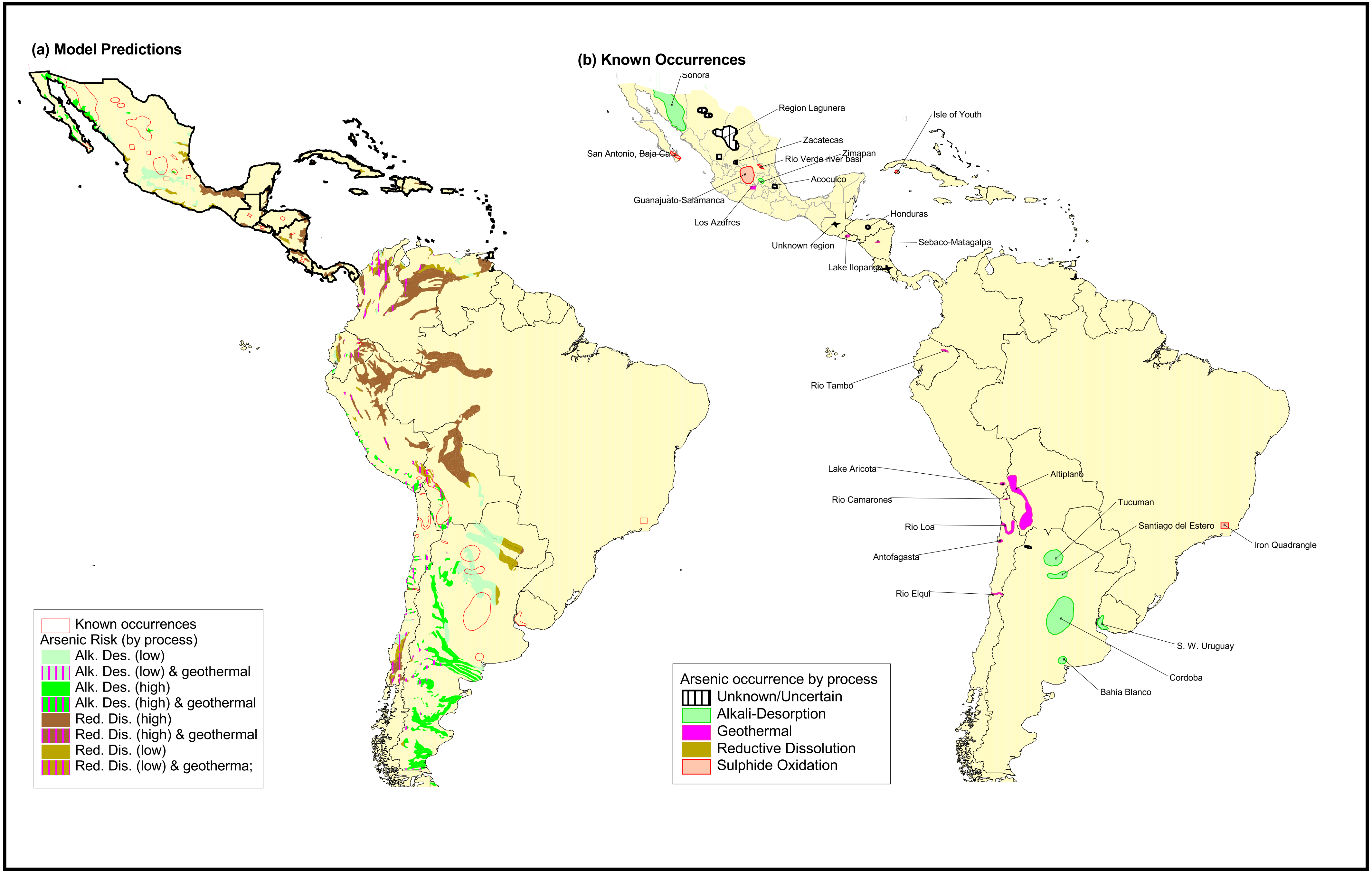


Fig. 7. Known and Predicted Distribution of Arsenic in South and Central America

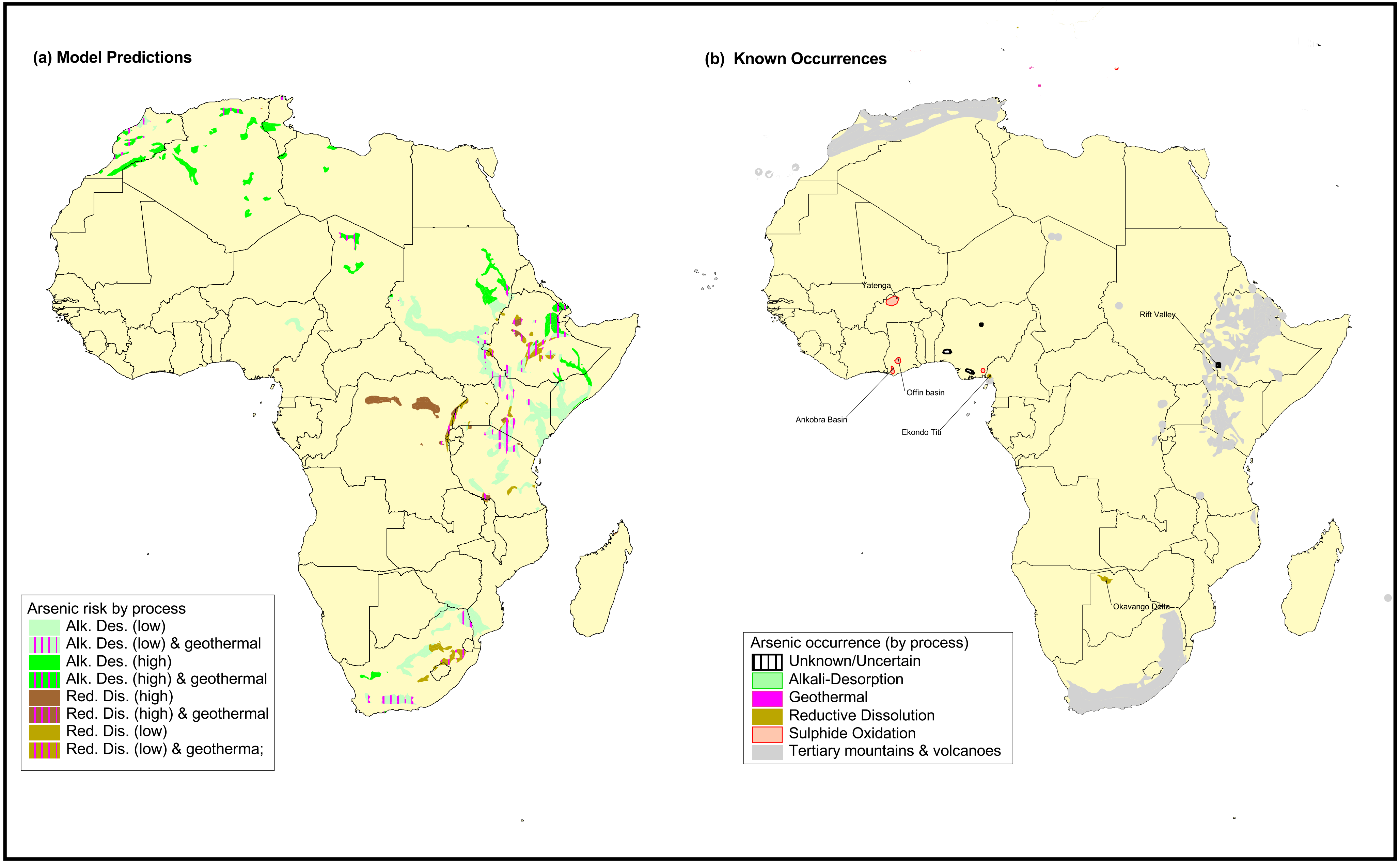


Fig. 8. Known and Predicted Distribution of Arsenic in Africa

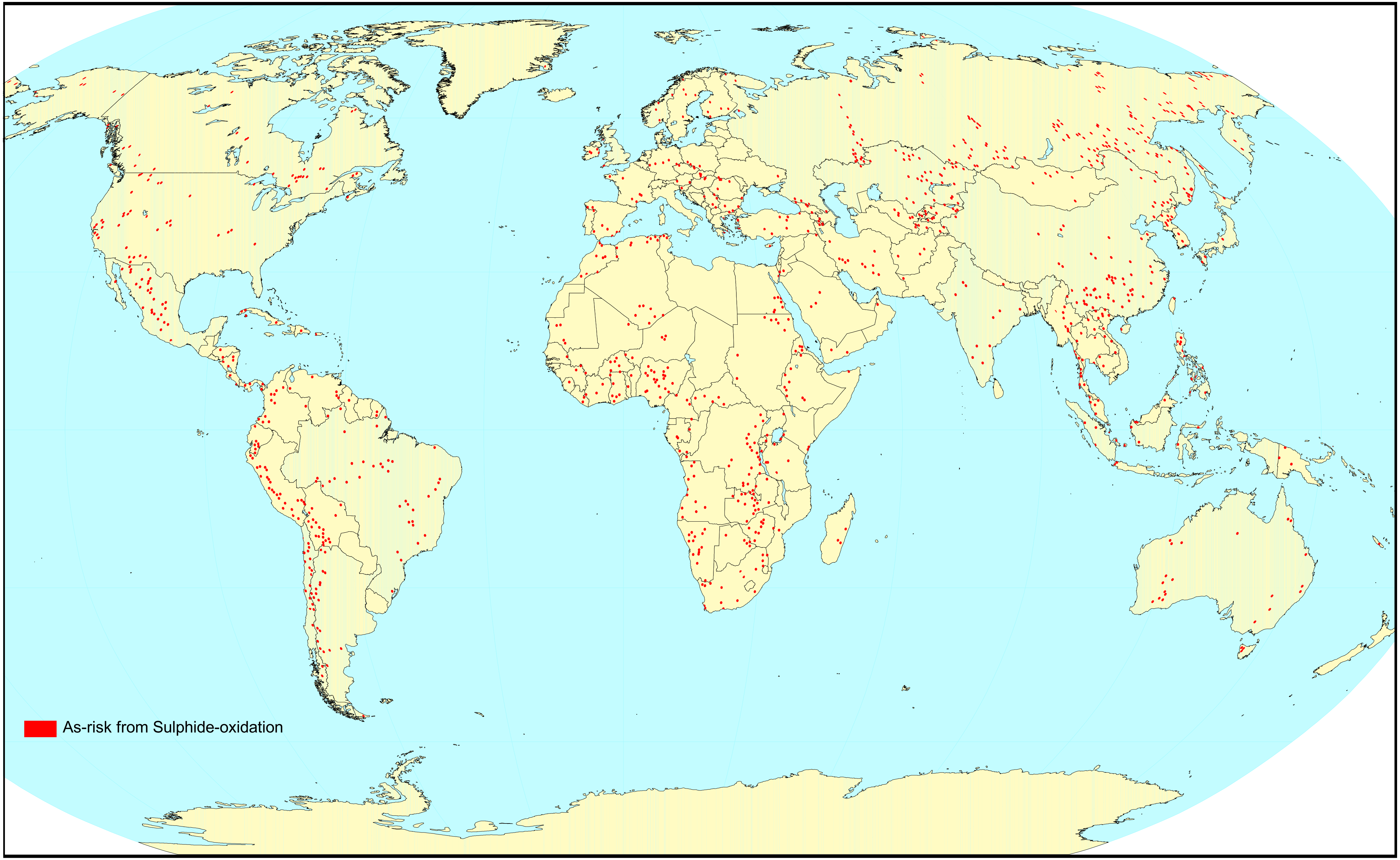


Fig. 9. Areas with a Risk of Arsenic Pollution due to Sulphide-oxidation

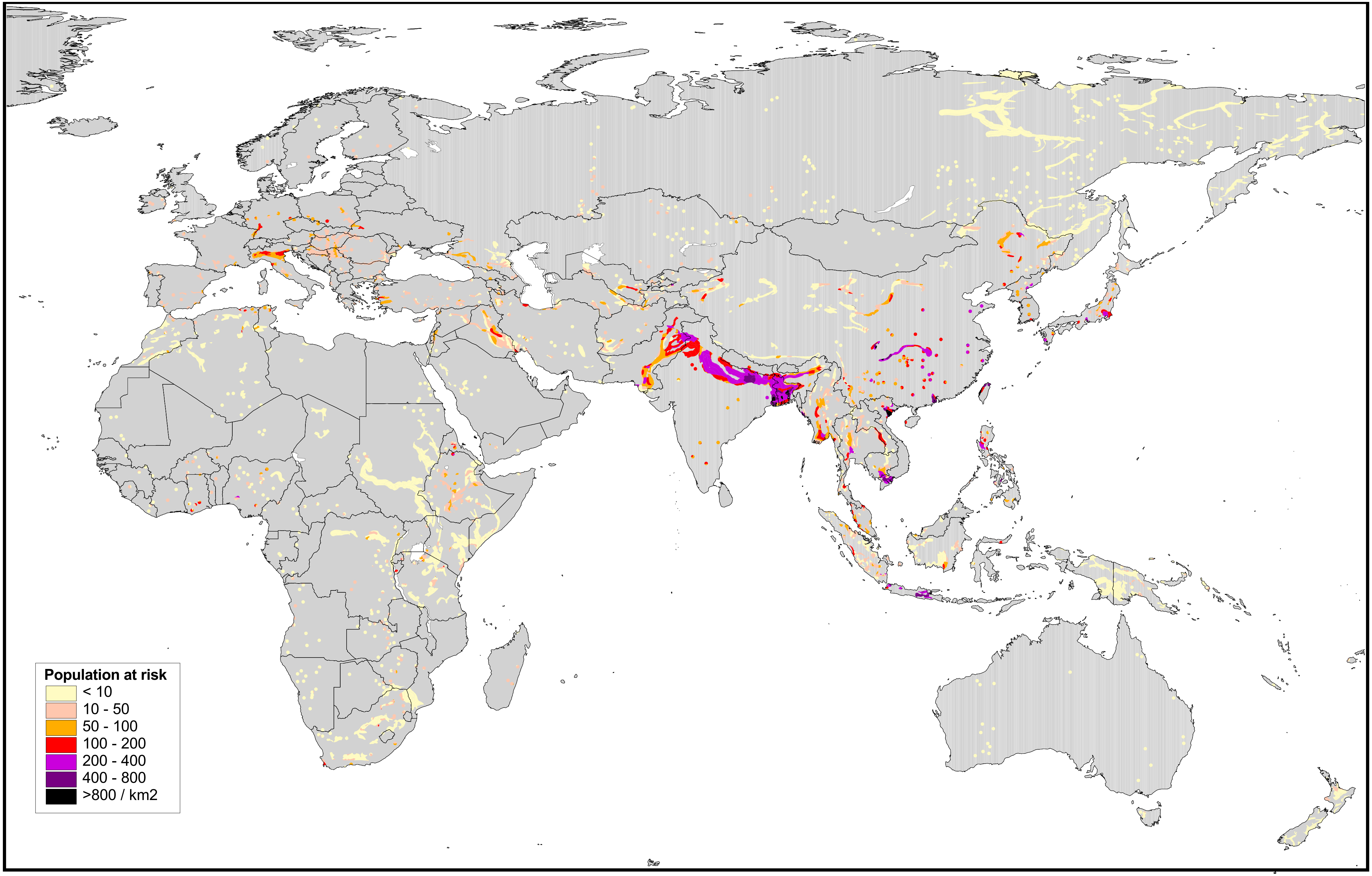


Fig. 10. Distribution of Population At Risk in the Eastern Hemisphere

Note: The map includes the risk of arsenic mobilsiation by sulphide oxidation

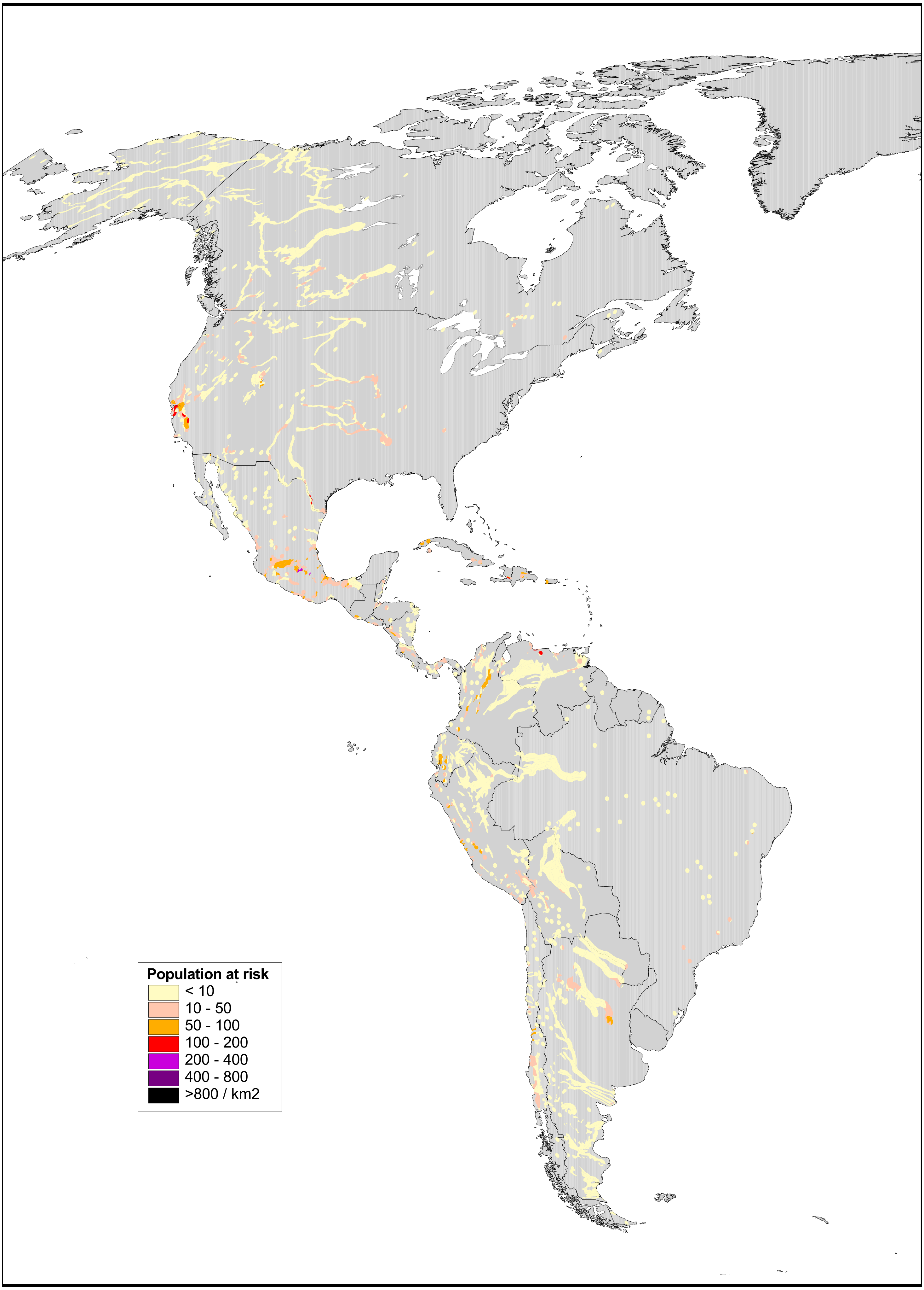
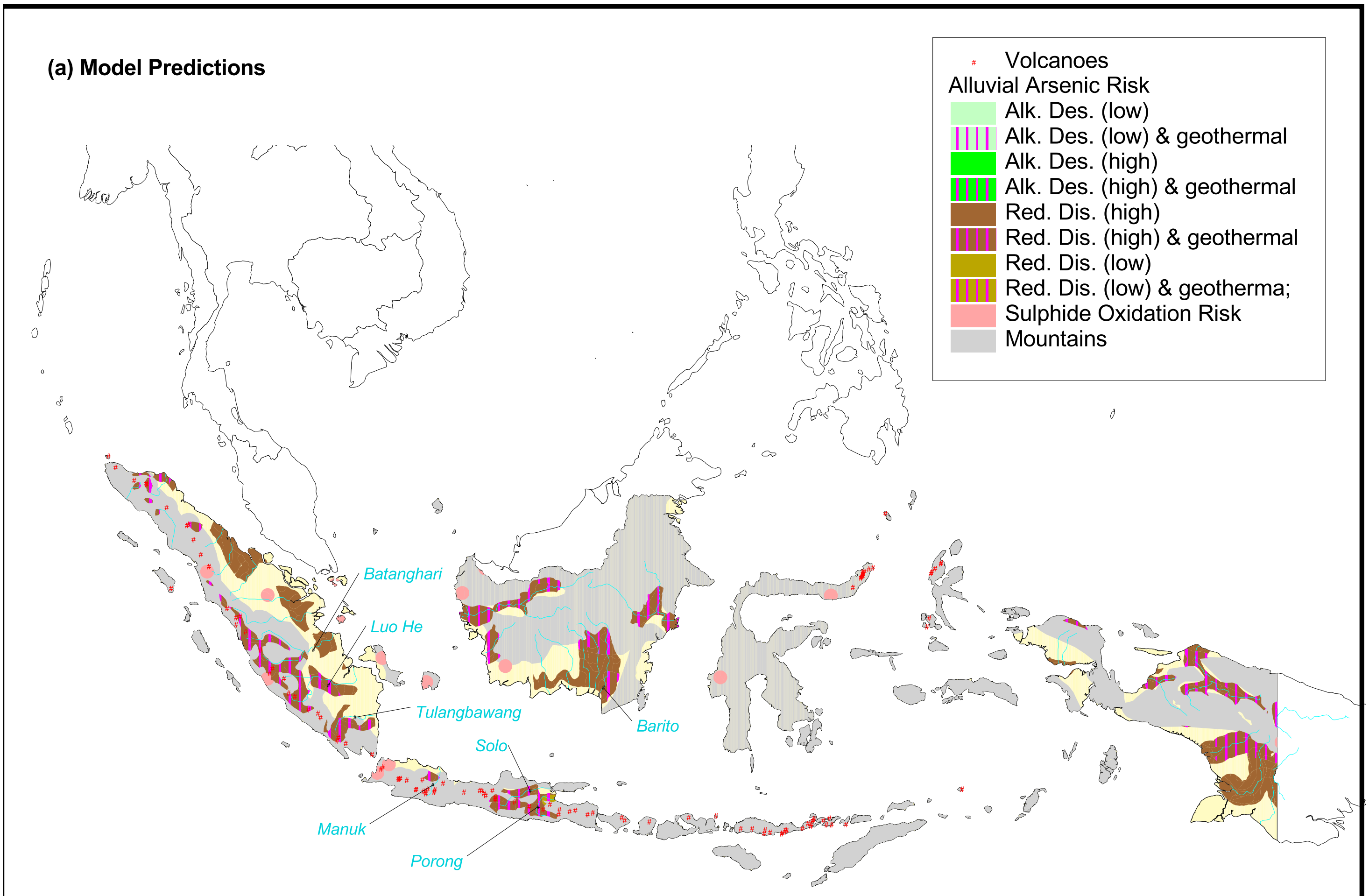


Fig. 11. Distribution of Population At Risk in the Western Hemisphere

Note: The map includes the risk of arsenic mobilsiation by sulphide oxidation

(a) Model Predictions



(b) Population at Risk

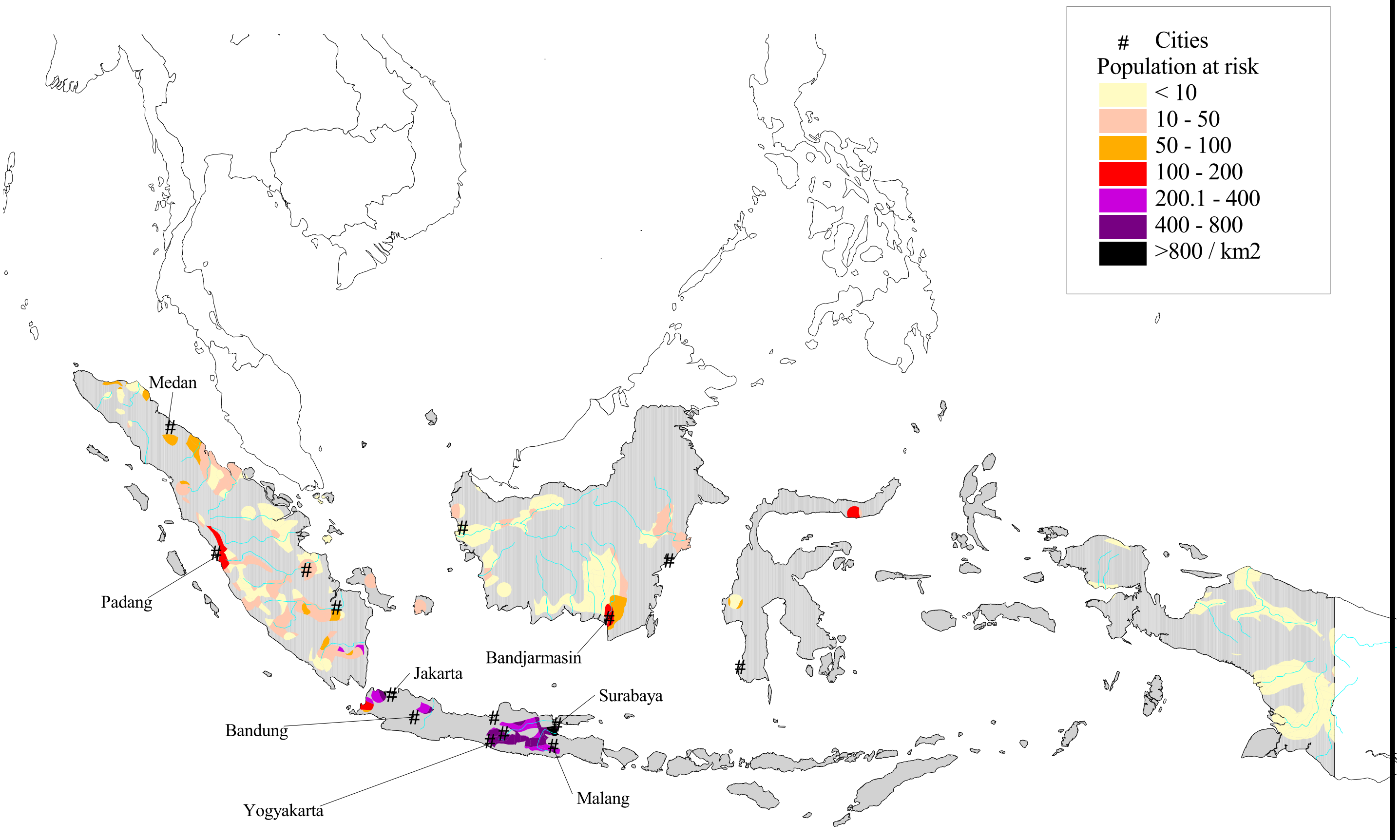
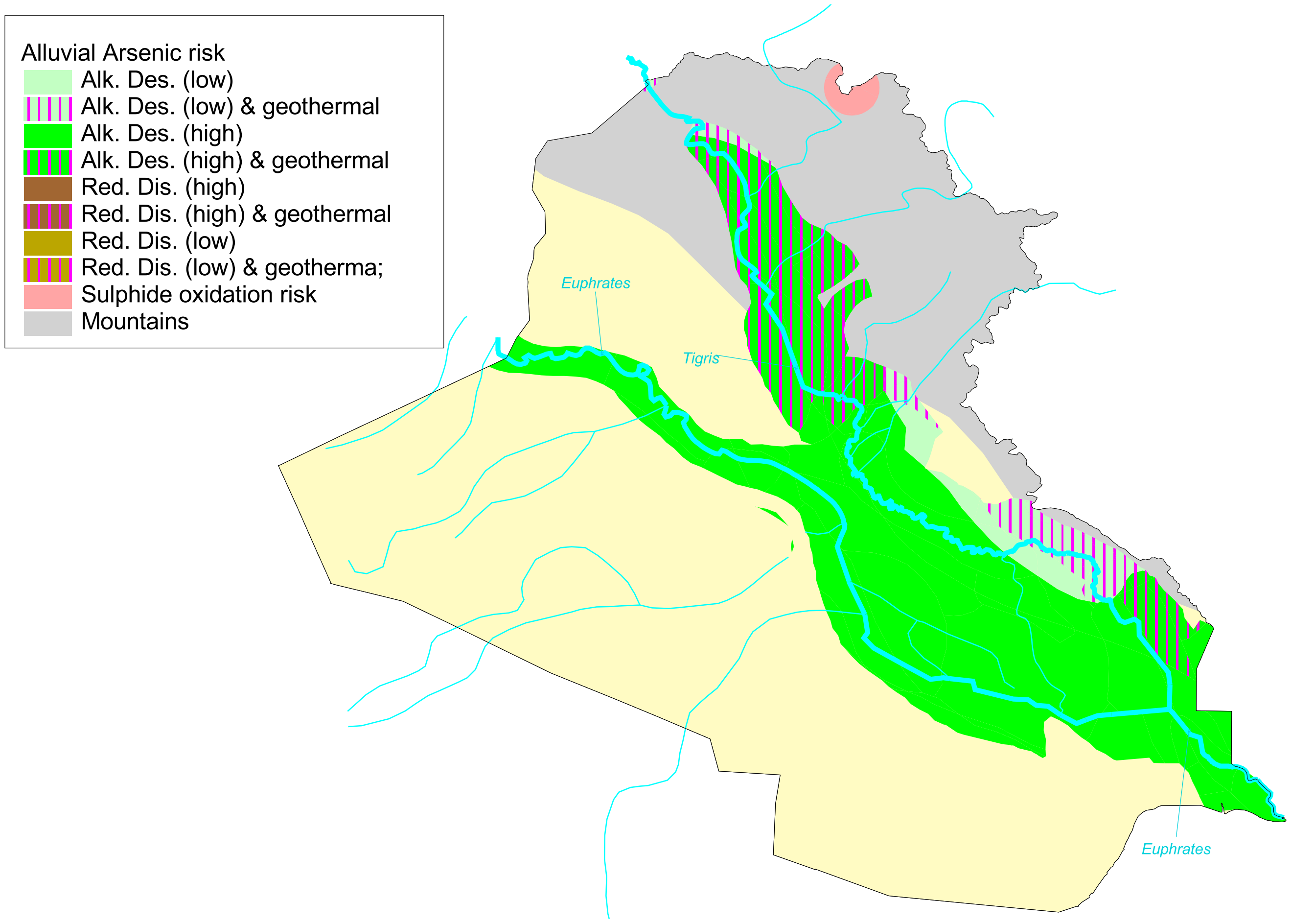


Fig. 12. Predicted Distribution of Arsenic and At-Risk Population in Indonesia

(a) Model Predictions



(b) Population at Risk

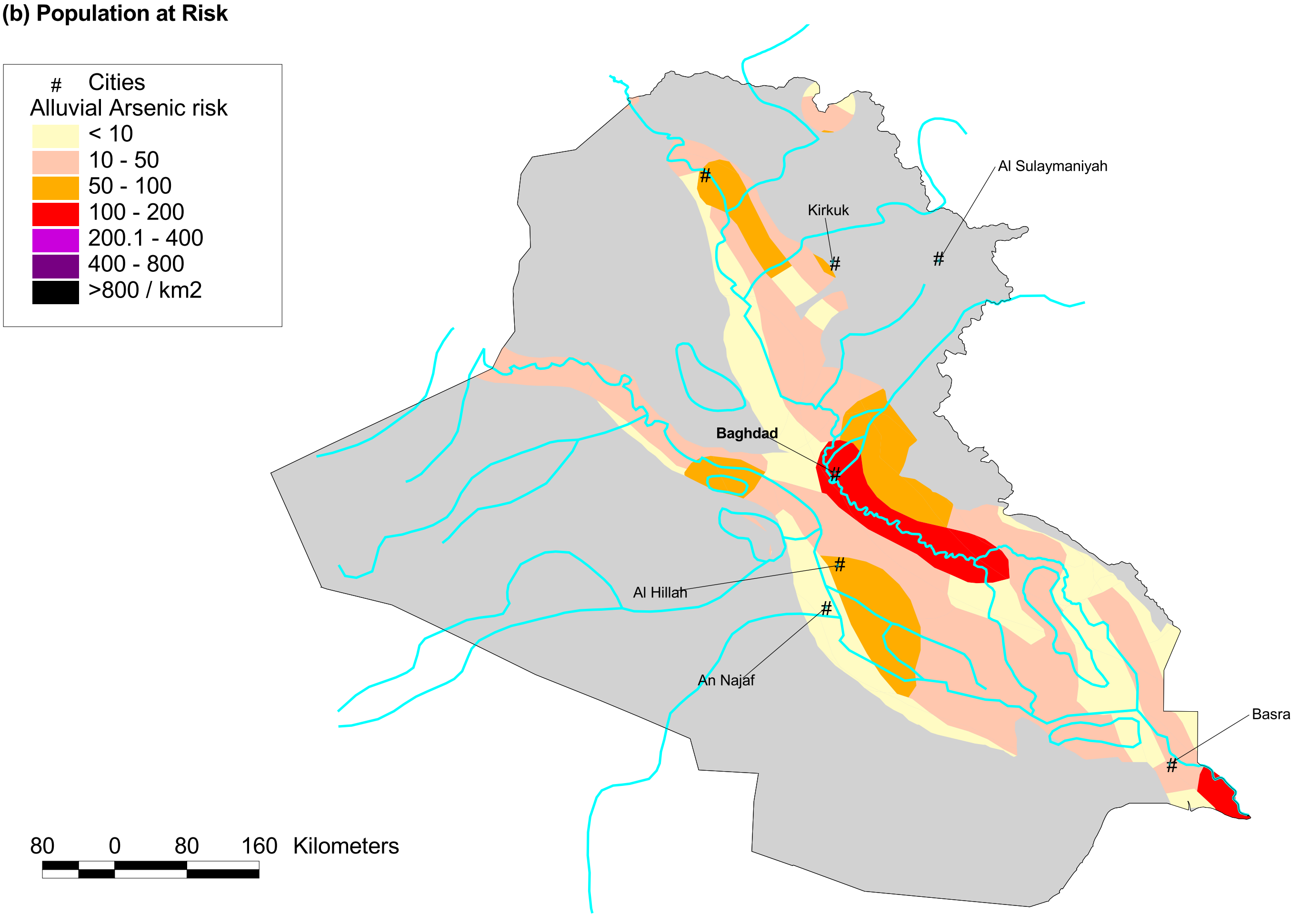


Fig. 13. Predicted Distribution of Arsenic and Population At Risk in Iraq

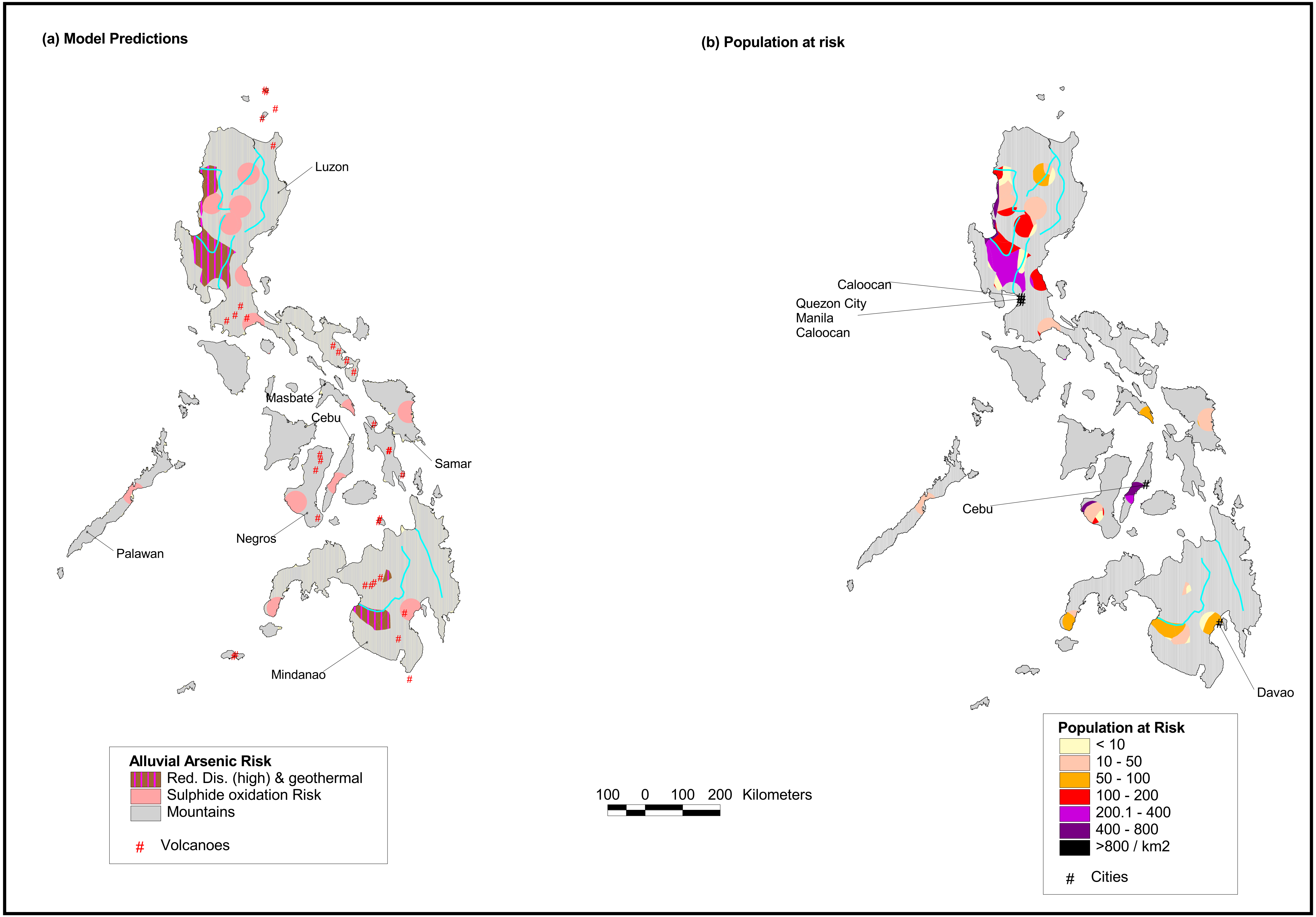
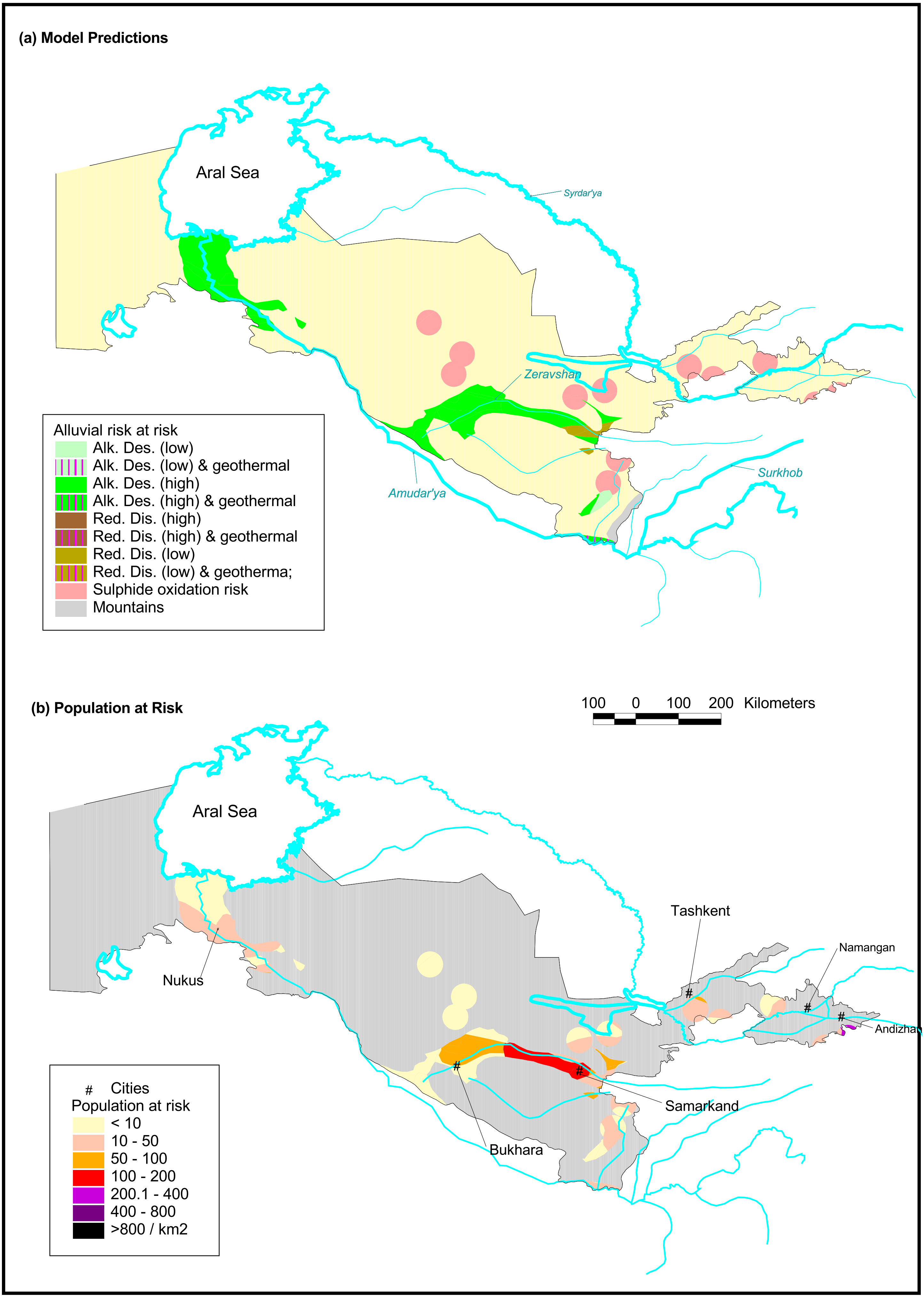


Fig. 14. Predicted Distribution of Arsenic and Population At Risk in the Philippines



(a) Model Predictions

(b) Population at Risk

Fig. 15. Predicted Distribution of Arsenic and Population At Risk in Uzbekistan

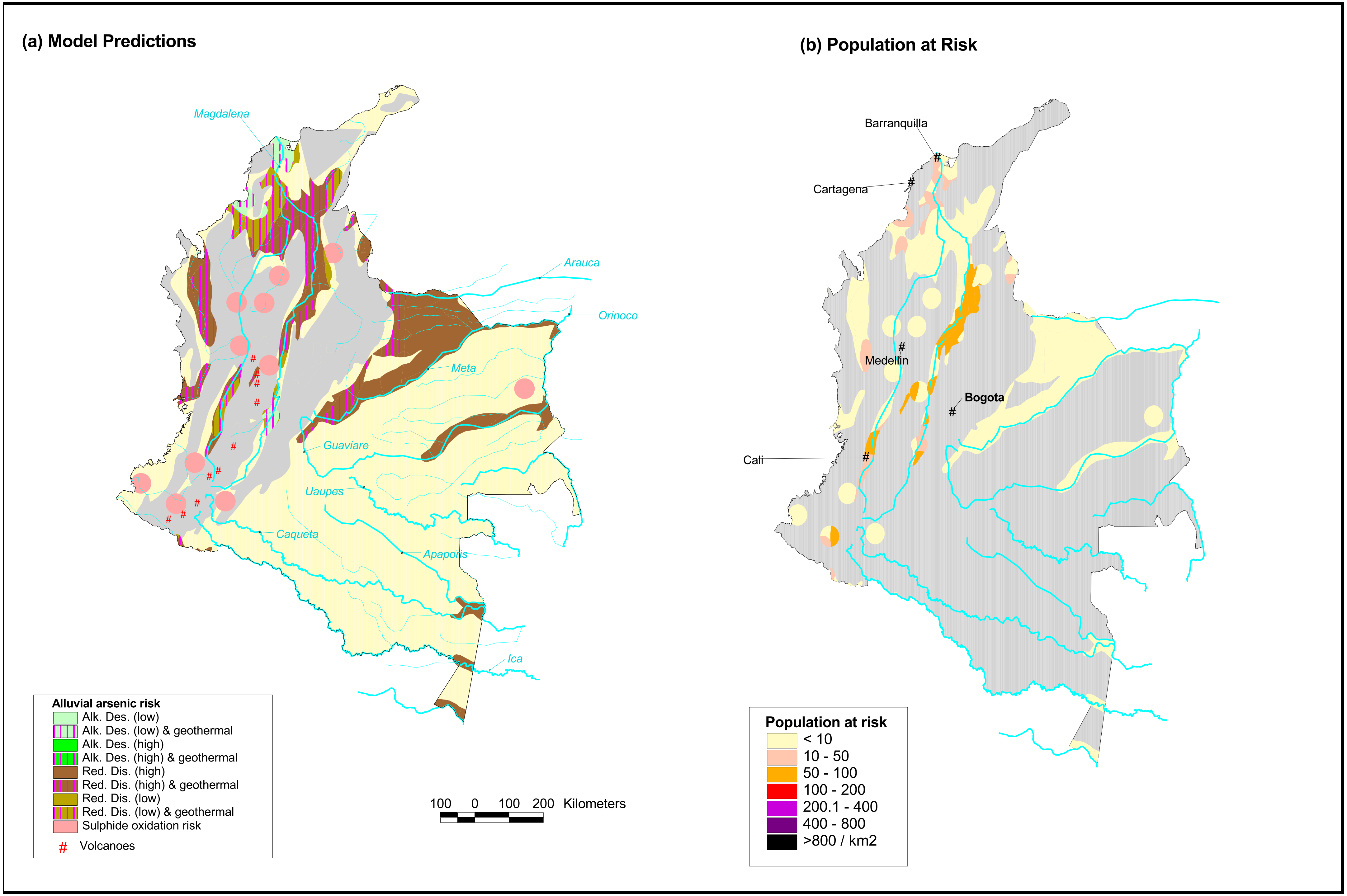
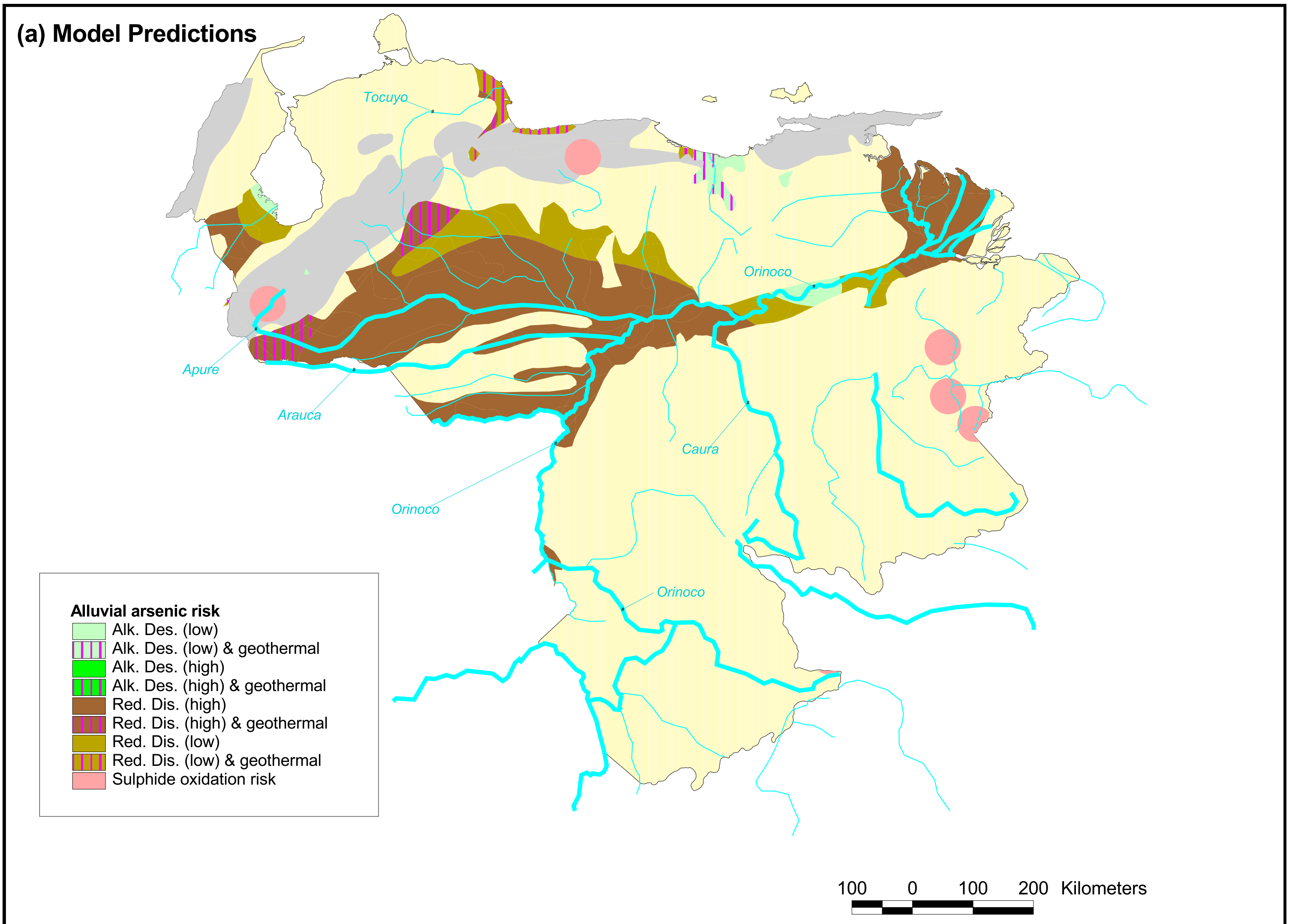


Fig. 16. Predicted Distribution of Arsenic Pollution and Population at Risk in Colombia


(a) Model Predictions

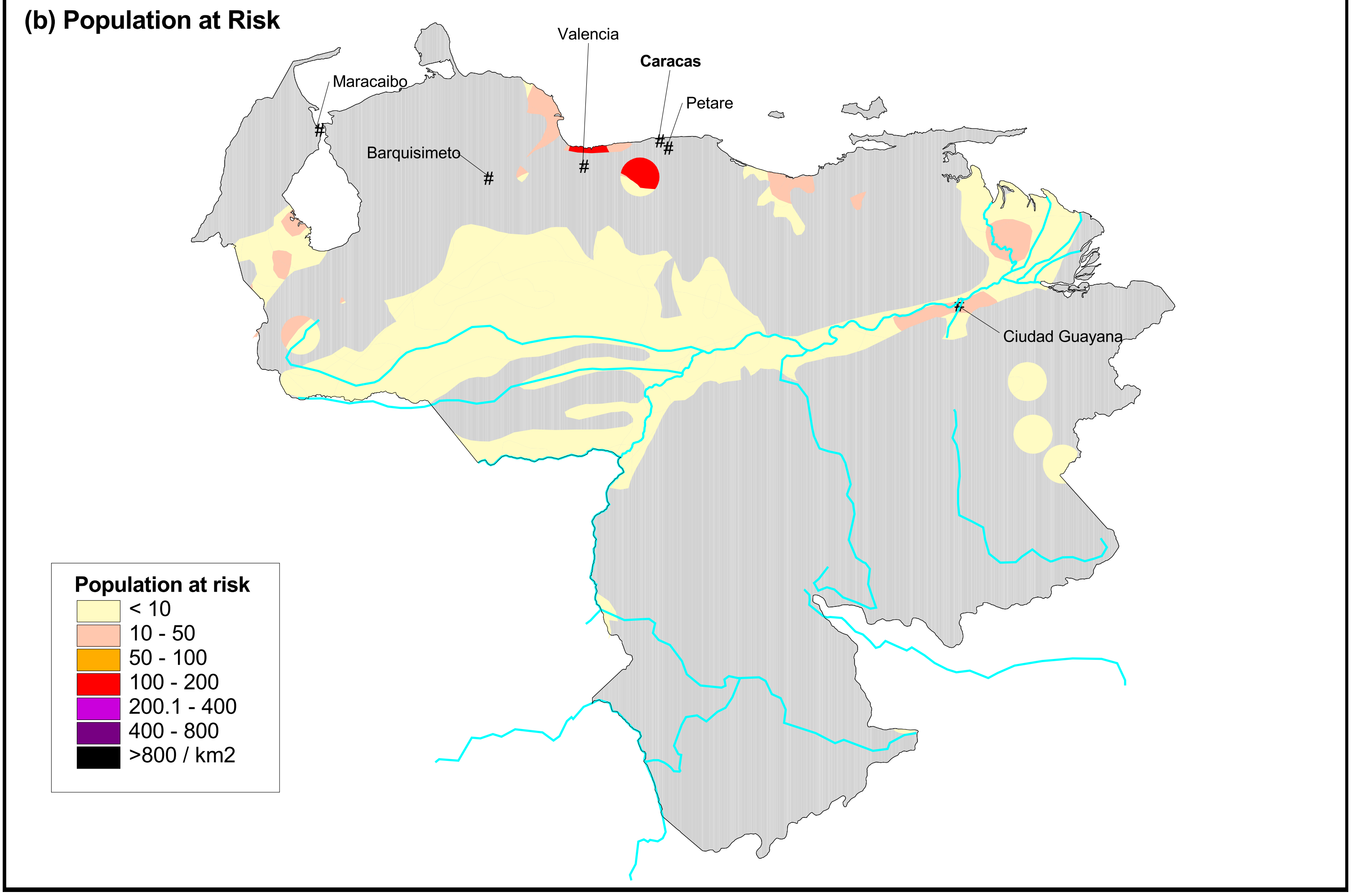
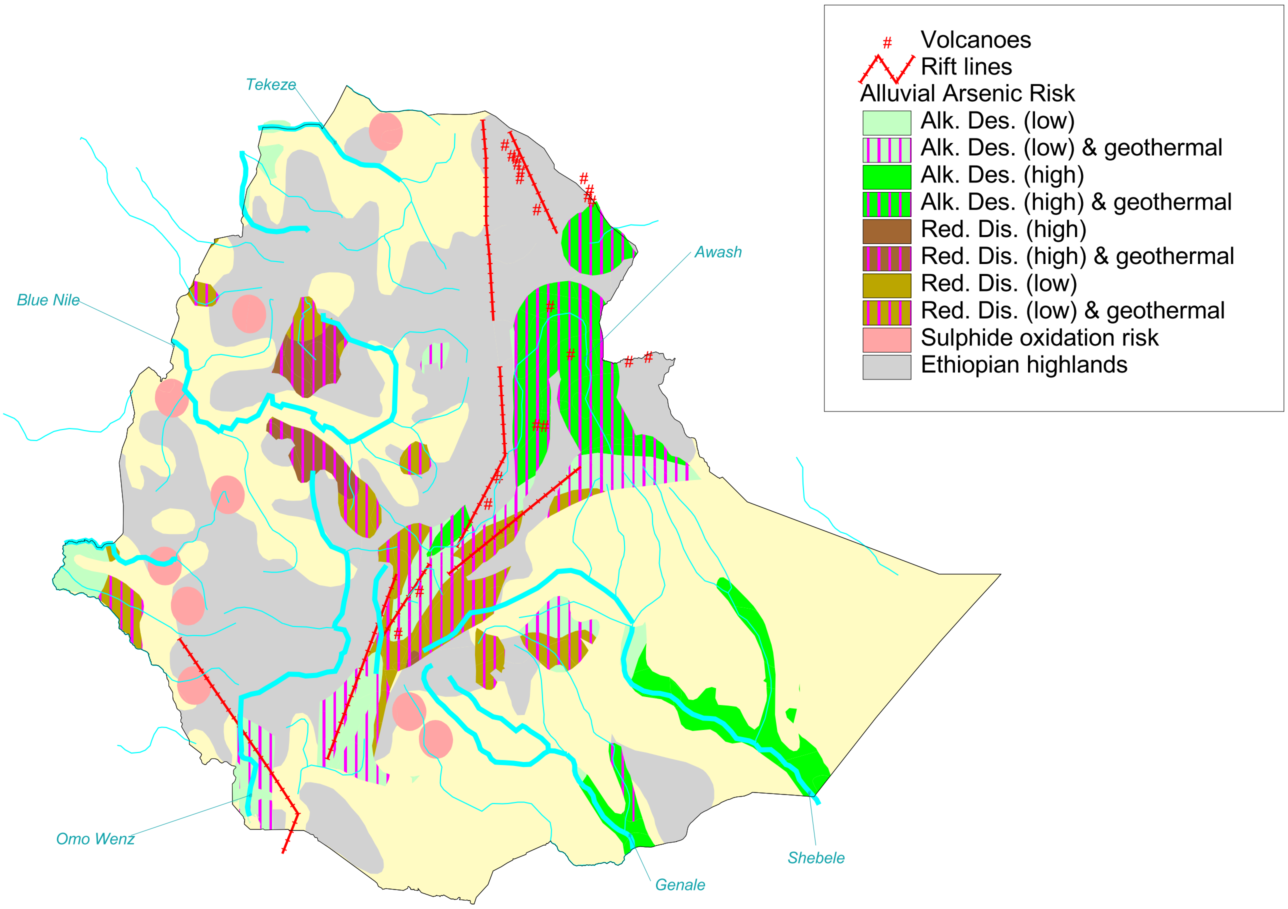

(b) Population at Risk

Fig. 17. Predicted Distribution of Arsenic Pollution and Population at Risk in Venezuela

(a) Model Predictions



(b) Population at Risk

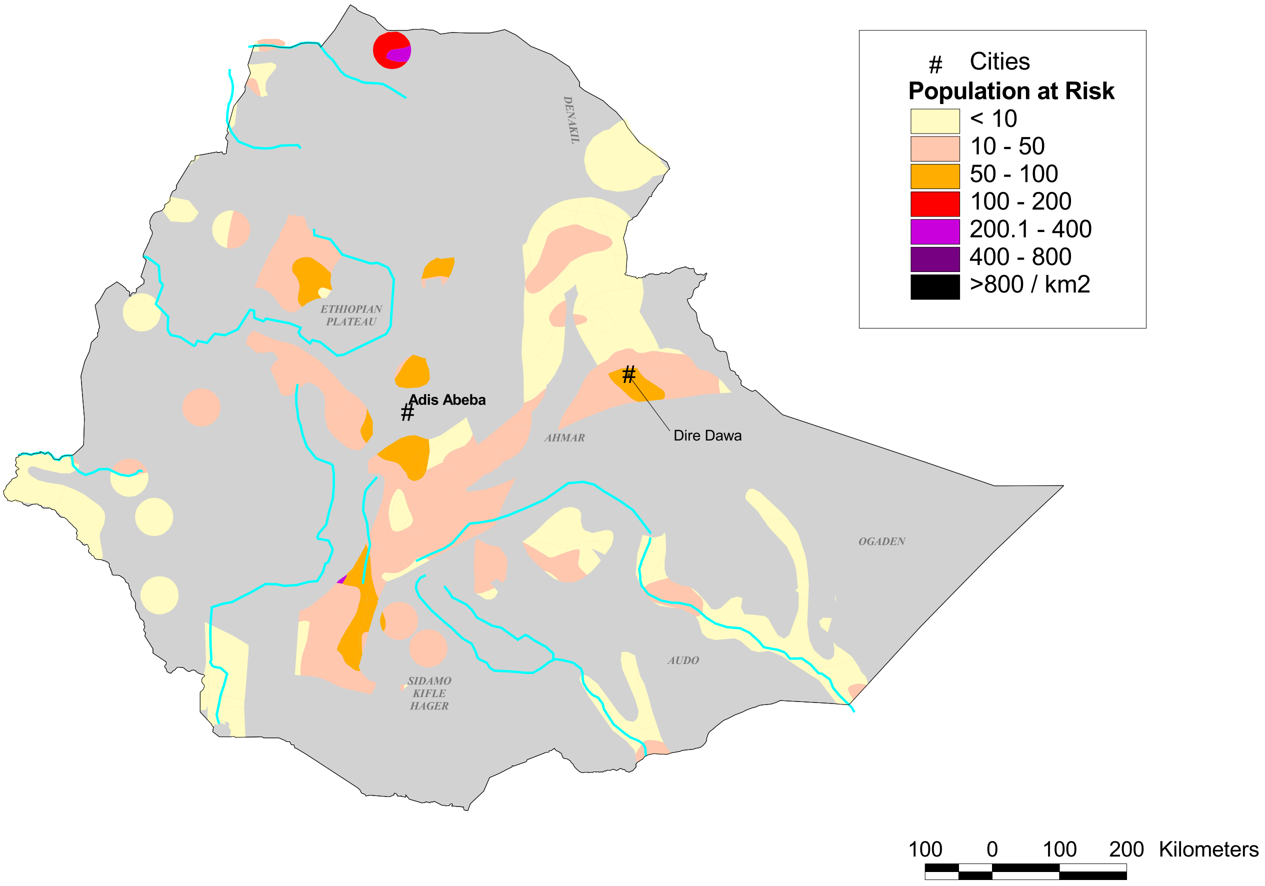


Fig. 18. Known and Predicted Distribution of Arsenic in Ethiopia

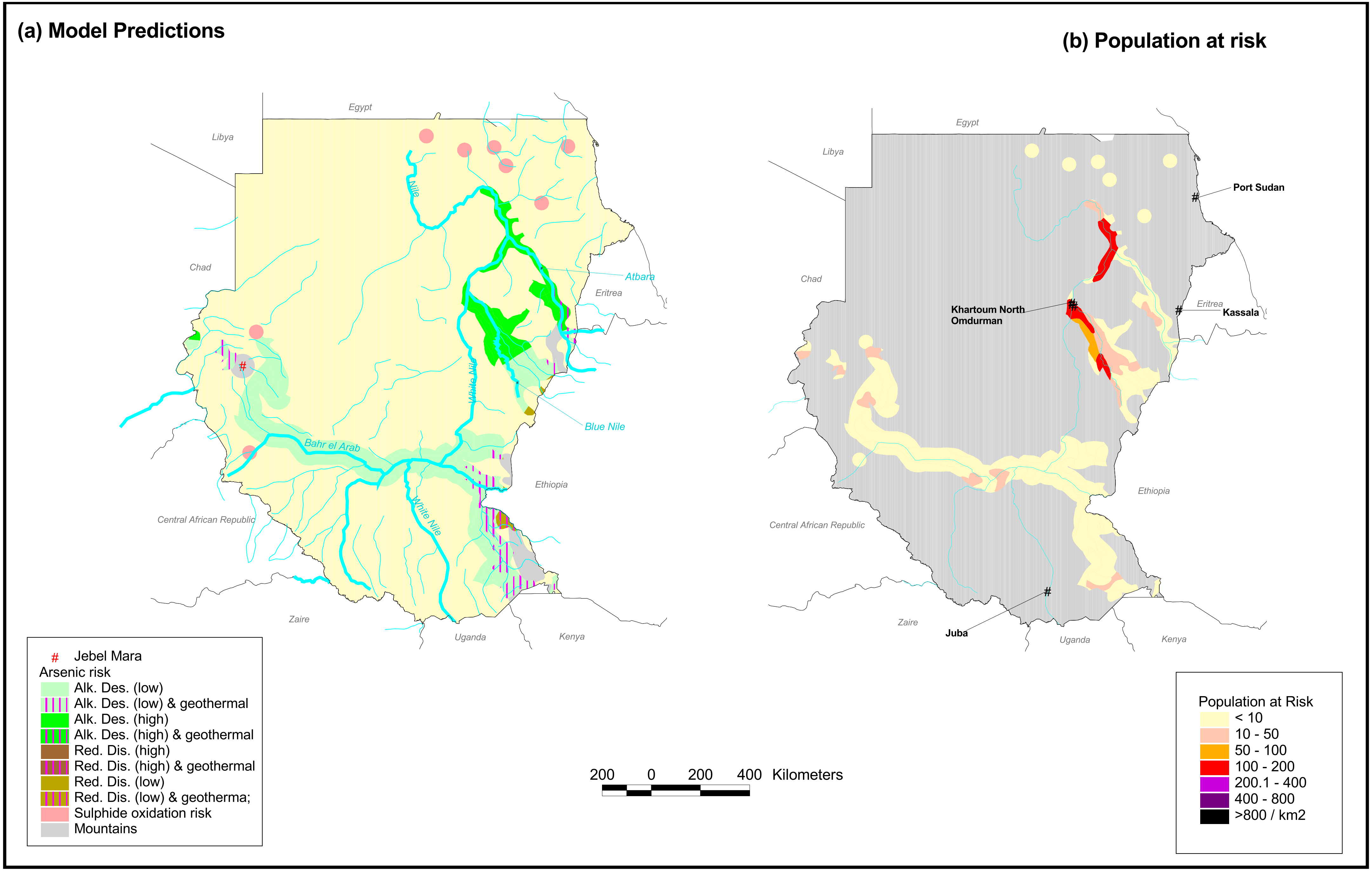
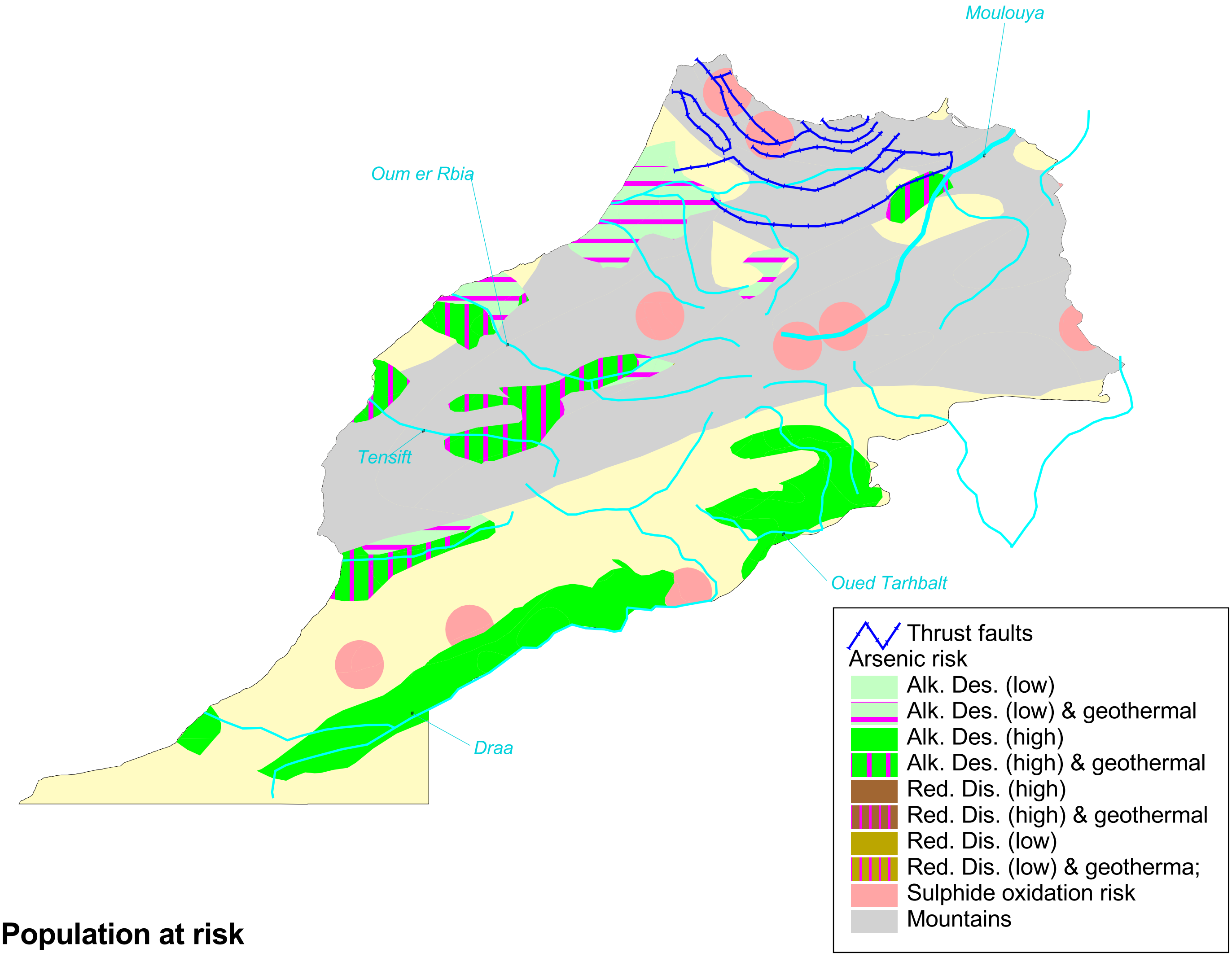


Fig. 19. Predicted Distribution of Arsenic and Population At Risk in Sudan

(a) Model Predictions



(b) Population at risk

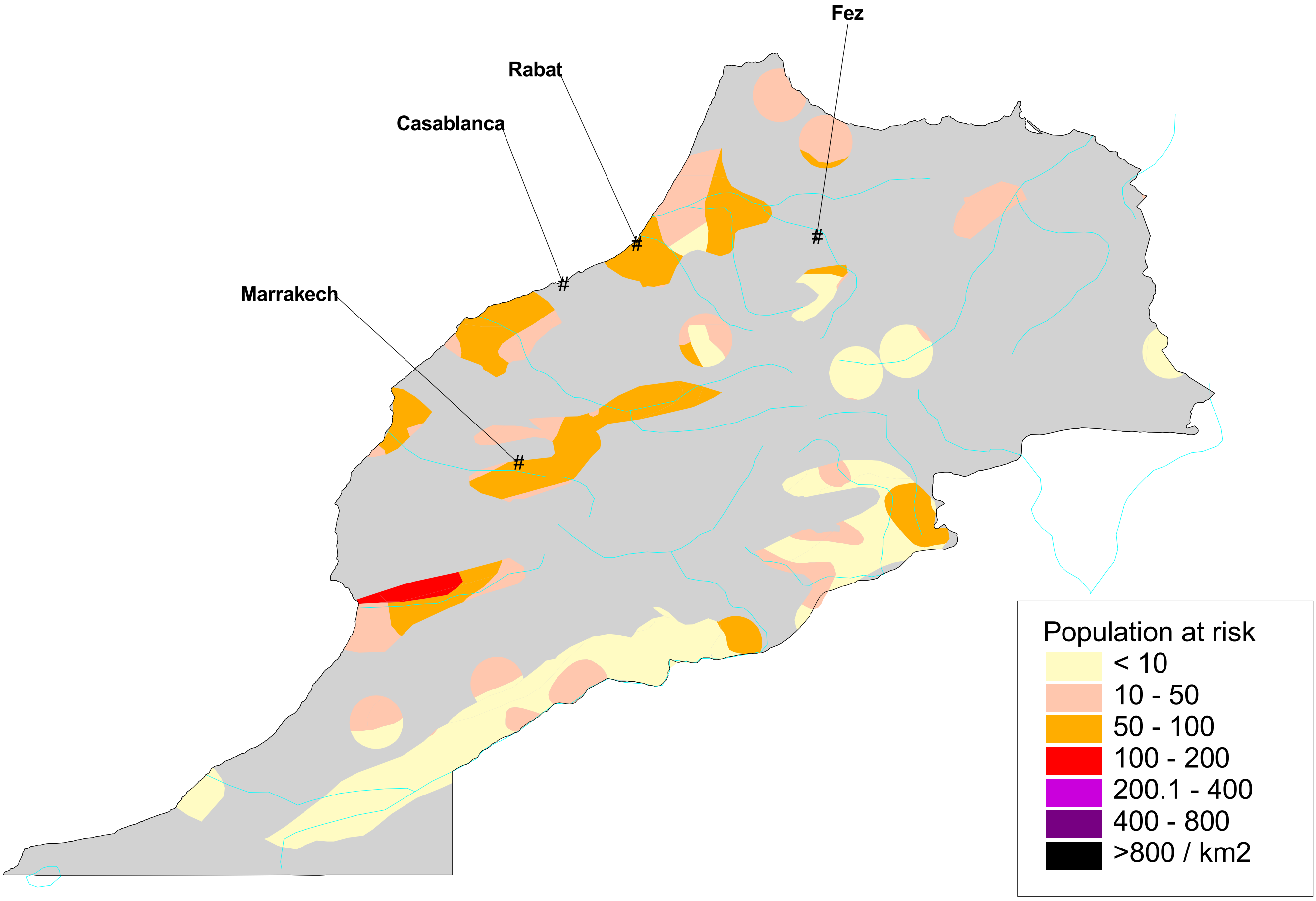


Fig. 20. Predicted Distribution of Arsenic and Population At Risk in Morocco

APPENDICES

APPENDIX I:

Known Cases of Arsenic Contamination

Ref. Nr	Country	Location
AFRICA		
1	Botswana	Okavango Delta
2	Burkina Faso	Yatenga
190	Cameroon	Ekondo Titi
3	Ethiopia	Rift Valley
18	Ghana	Offin basin
235		Ankobra Basin
5	Nigeria	Kaduna
6		Ogunstate
7		Rivers State
8		Wari - Port Harcourt
AUSTRALASIA		
60	Australia	Perth
61		Stuarts Point, NSW
62	New Zealand	Waikato River
63		Waiotapu valley
64		Wairu Plain
237		N. Hawkes bay
238		Wanganui
239		Gisborne
240		Bay of Plenty
ASIA		
9	Afghanistan	Logar and Ghazni
10	Bangladesh	Chittagong coastal plain
11		Bengal Basin
12	Cambodia	Cambodia
13	China	Datong Basin
14		Houshayu, nr Beijing
15		Inner Mongolia
16		Jilin Province
17		Jinchuan, Sichuan
18		Liaoning Province
19		Linbei, Wuhe, Anhui
20		Ningxia Province
21		Qinghai-Tibet Platea
22		Shanxi
23		Tongxiang, Zhejiang
24		Weichang, Hebei
25		Xinjiang province
26		Zhongmou, Zhengzhou
209		W. Xinjiang - Tarim
210		Yunnan N
211		Yunnan S
212-214		Inner Mongolia
27	India	Assam
28		Chandigarh
29		Chattisgarh
30		Himachal Pradesh
31		Nagaland
32		Thoubal (Manipur)
33		Tripura
34		Vapi (Gujarat)
153		Chenai
157		Uttar Pradesh
35	Indonesia	Citarum River
203		Aceh
36	Iran	Kurdistan
37	Japan	Fukui
38		Fukuoka - Kumamoto
39		Niigata Plain
40		Osaka
41		Sendai
42		Shinji Plain
43		Takatsuki
44	Kazakhstan	South Mangyshlak
ASIA (continued)		
201	Lao PDR	Inchampasak & Sarava
202		Attapeu province
45	Malaysia	Kampong Sekolah
232	Mongolia	Dornod Steppe
233		Gobi Altai - Hovd
234		Arkhangai
46	Myanmar	Irrawaddy Delta
154-5	Nepal	Terai
156		Kathmandu Valley
47-49	Pakistan	Indus valley
158	Philipinnes	Mount Apo
159		Greater Tongonan
88	Russia	Sakhalin
231	Saudi Arabia	Jubail
50	Sri Lanka	Near Colombo
51	Taiwan	N E Taiwan
52		SW Taiwan
53	Thailand	Hat Yai
54		Nakorn Chaisi
55		Tin Belt
56	Turkey	Afyon, Heybeli Spa
57		Emet-Hisarcik
236		Nif mountain
58	Vietnam	Mekong
59		Red River
245	South Korea	southwest
EUROPE		
192	Belgium	Neogene, Flanders
65	Croatia	Eastern Croatia
163	Czech Republic	Celina-Mokrsko
66	Denmark	Fensmark
67	Finland	Finnish Lapland
68		SW Finland
69	France	Aquitaine
70		Massif Central
71		Pyrenees
72		Vosges Mts
152		Centre
164		W-C France
73	Germany	Bavaria
74		Paderborn
75		Wiesbaden
76	Greece	E. Thessaly
77		Thessaloniki
227		Chalkidiki
78	Hungary	Tisza interfluve
151		SW Hungary
160		Danube valley
161-2		W. Hungary
162		
229	Ireland	Unspecified
79	Italy	Anzasca Valley, Piem
80		Etna
81		Siena
82		Stromboli / Vulcano
83		Vesuvius
166		Po Basin
191		Tiber valley
194		Emilia-Romagna
195		Lombardia
196		Veneto
197		Toscana
198		Lazio
199		Ischia

Ref. Nr	Country	Location
EUROPE (continued)		
207	Lithuania	Lithuania
84	Netherlands	Gouda
165		Brabant
85	Norway	Unspecified
230	Poland	Sudetes Mts
86	Romania	Transyvania
87	Russia	East Caucusus Foothi
89		Trans-Baikal
90	Slovakia	E. Slovakia
222-6		Slovakia
91	Slovenia	Radovljica
92	Spain	Castellon-Valencia
93		Duero Basin
94		Madrid Basin
206		Salamanca
95	Sweden	S. Sweden
96		Uppsala
215	Switzerland	Malcantone watershed
97	UK	Bridgwater
98		Severn Trent area
216		North Humberside
217		Liverpool-Rufford
218		Manchester-E.Cheshir
219		Vale of York
220		Carlisle Basin
246	Serbia	Northern Serbia
NORTH AMERICA		
99	Canada	Bowen Island
100		Cobalt, Ontario
101		Madoc, Ontario
102		Nova Scotia
103		Saskatchewan
104		Sunshine Coast/Powe
200	Cuba	Isle of Youth
106	Mexico	As area (Simeonova,
106		As area (Simeonova,
110		Region Lagunera
111		Guanajuato-Salamanca
112		Rio Verde river basi
113		San Antonio, Baja Ca
114		Sonora
115		Zimapan
241		Acoculco
242		Los Azufres
243		Guadiana
244		Zacatecas
107	USA	Grass Mt, S Dakota
116		California
117		Sierra Nevada
118		Cook Inlet basin
119		Dakota
120		Fairbanks, Alaska
121		Idaho
122		Illinois
123		Michigan
124		Minnesota, Iowa
125		N. Idaho
126		Nebraska
127		New England
128		Oklahoma
129		Rio Grande
NORTH AMERICA (continued)		
130		SW USA
131		Washington State
132	USA	Williamette Bsn, Oregon
133		Wisconsin
167		Kansas
168		Nebraska
169		Colorado
170		Washington
171-2		Oregon
173-4		Nevada
175		Carson Desert, Nevada
176		Yellowstone
177		Arizona
178		Ohio
179		Indiana
180		Florida
181		Arkansas
182		Idaho
183-4		Montana
185		Kentucky
186		Utah
187		Washington
188		San Joaquin valley
193		Owens Lake
228		Newark basin
SOUTH AMERICA		
134	Argentina	Bahia Blanco
135		Tucuman
136		Cordoba
137		San Antonio de los J
138		Santiago del Estero
139	Bolivia	Altiplano
140	Brazil	Iron Quadrangle
141	Chile	Antofagasta
142		Rio Camarones
143		Rio Elqui
144		Rio Loa
145	Costa Rica	Unknown region
146	Ecuador	Rio Tambo
147	El Salvador	Lake Ilopango
148	Guatemala	Unknown region
204	Honduras	Honduras
149	Nicaragua	Sebaco-Matagalpa
150	Peru	Lake Aricota
221	Uruguay	S. W. Uruguay
OCEANIA		
208	Guam	Tumon Bay
189	Iceland	Iceland
188	USA	Hawaii

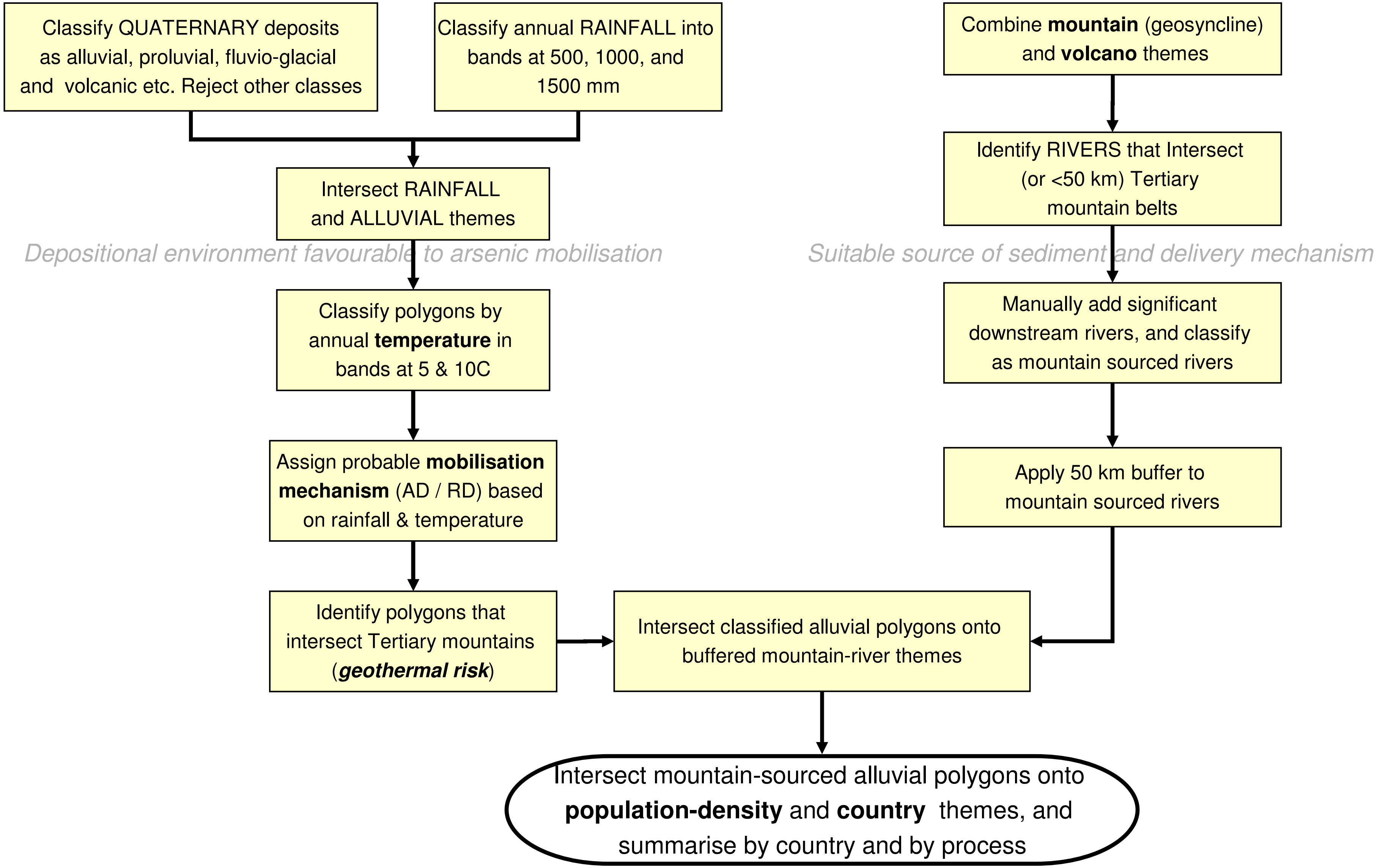
Source: Ravenscroft et al. (2008)

APPENDIX II

FLOWCHARTS FOR GIS DATA PROCESSING

A GIS Model for Alluvial Arsenic Risk

(based on the ESRI ArcAtlas data set)



Classify QUATERNARY deposits as alluvial, proluvial, fluvio-glacial and volcanic etc. Reject other classes

Classify annual RAINFALL into bands at 500, 1000, and 1500 mm

Intersect RAINFALL and ALLUVIAL themes

Depositional environment favourable to arsenic mobilisation

Classify polygons by annual **temperature** in bands at 5 & 10C

Assign probable **mobilisation mechanism** (AD / RD) based on rainfall & temperature

Identify polygons that intersect Tertiary mountains (***geothermal risk***)

Combine **mountain** (geosyncline) and **volcano** themes

Identify RIVERS that Intersect (or <50 km) Tertiary mountain belts

Suitable source of sediment and delivery mechanism

Manually add significant downstream rivers, and classify as mountain sourced rivers

Apply 50 km buffer to mountain sourced rivers

Intersect classified alluvial polygons onto buffered mountain-river themes

Intersect mountain-sourced alluvial polygons onto **population-density** and **country** themes, and summarise by country and by process

A GIS Model for Arsenic Risk from Sulphide Oxidation
(based on the ESRI ArcAtlas data set)

Eliminate non-sulphidic ore deposits. Delete: ferrous, fuels, gems, non-metals, sedimentary and weathering deposits

Select ‘elements’ likely to be associated with arsenic: Au, Ag, Cu, Hg, Pb, Sb, Sn & As

Apply 30 km buffer around selected deposits

Remove overlap with areas of alluvial risk

Intersect output onto **population density** and **country** themes. Evaluate at-risk population