Threat of Arsenic to Agriculture in India, Bangladesh and Nepal

Hugh Brammer

Arsemic-polluted water used for irrigation in certain areas of India, Bangladesh and Nepal is posing a health hazard for people eating food from the crops irrigated. The accumulation of arsenic in the soil is a threat to sustainable agriculture in the areas affected. These problems are not yet widely recognised. Urgent action is required to address them. The most important need is to assess the scale of the problem so that appropriate interventions can be planned.

Natural arsenic pollution of drinking water supplies is now known to occur in over 70 countries, affecting an estimated 150 million people worldwide [Ravenscroft et al 2008]. Most of the people at risk live on the Indian sub-continent: an estimated 50 million in Bangladesh, 30 million in India and 2.5 million in Nepal. Pollution also occurs in some countries of east and south-east Asia. The problem of arsenic in drinking water is now well recognised and measures are being taken to mitigate it. However, it is now becoming apparent that arsenic-contaminated groundwater used for irrigation poses an equally serious health hazard for people eating food from the crops irrigated; also that arsenic accumulating in irrigated soils poses a threat to sustainable agriculture in affected areas [Heikens 2006]. These threats are not yet widely recognised in the affected countries or by international aid agencies and little work has been done to assess the scale of the problem or to identify and test possible mitigation measures. This article first outlines important characteristics of arsenic accumulation in soils and crops, then describes possible mitigation measures that require testing for use in different environmental conditions.

1 Arsenic Contamination

In this section, we outline the characteristics of arsenic contamination in the soil and in crops in the affected areas of the three countries.

1.1 Areas Affected

The figure (p 80) shows the areas of India, Bangladesh and Nepal within which arsenic contamination of groundwater used for drinking has been reported. Where irrigation water and drinking water are drawn from the same polluted aquifers, it may provisionally be assumed that the irrigation water is also polluted. In Bangladesh and West Bengal, about 90 per cent of the groundwater that is abstracted is used for irrigation. It comes from aquifers between ca 20 and 120 m in young (Holocene) alluvial sediments. Such floodplain sediments extend up the Ganges floodplain into Bihar. In northern India and Nepal, the contaminated aquifers are in piedmont fan deposits in the terai zone at the foot of the Himalayas; they also occur in the Kathmandu valley. In central India (Chhattisgarh), the contaminated groundwater is in sediments derived from ancient volcanic rocks [Patel et al 2005].

The arsenic pollution of groundwater is natural. It is not due to human activities. The arsenic originates in relatively unweathered sediments derived from igneous and metamorphic rocks. Arsenic is not present in large amounts in these sediments: its importance lies in the toxicity of this element at very low concentrations. Arsenic is originally bound with iron in sediment particles. It is released into groundwater where microbial activity in organic matter (for example, in buried peat layers) reduces iron to the ferrous form. The variable content of organic matter in aquifer sediments, both laterally and vertically, probably accounts for the great variations between tubewells in the arsenic concentrations of the groundwater they deliver. Great variations also occur between areas in the iron-arsenic and phosphorus-arsenic ratios in groundwater. These differences may be significant for arsenic accumulation rates in soils, plant uptake and feasible mitigation measures.

1.2 Arsenic in Groundwater

Arsenic in irrigation water is much more difficult to deal with than the problem of arsenic in drinking water. Arsenic uptake by soils and crops is highly complex. That is particularly so in soils used for transplanted rice (paddy), which have been little studied so far. Complexities that need to be recognised in organising survey, research and mitigation programmes are outlined below.

Arsenic concentrations vary greatly between tubewells. In Bangladesh in 1998, 25 per cent of domestic wells provided...
water that exceeded the national drinking water standard of 50 parts per billion (ppb) (µg/l) arsenic and approximately twice that proportion exceeded the World Health Organisation (WHO) standard of 10 ppb [Ravenscroft et al 2005]. Similar proportions were reported from nine arsenic-affected districts of West Bengal [Uchino et al 2006]. In affected areas, the proportion of wells within villages that exceed the national standard can range between >90 per cent and <10 per cent. Arsenic concentrations as high as 510 ppb have been recorded in Bangladesh [Islam et al 2007] and 2,629 ppb in Nepal [Shresta et al 2003].

1.3 Arsenic in Soils

1.3.1 Environmental Diversity

Floodplains and piedmont plains are not as uniform in relief and soils as is often assumed. In Bangladesh, for example, there are significant differences between the Ganges, Brahmaputra, Meghna, Tista and other floodplains and differences also between younger and older parts of these floodplains. Within floodplains, there are significant local differences in soil and flooding conditions: for instance, on the Ganges river floodplain, ridges (old river banks) are shallowly or non-flooded and have loamy, calcareous soils low in organic matter, whereas adjoining basins are seasonally deeply flooded and have heavy clays with a strongly acid, humus-rich topsoil. Such local differences influence arsenic accumulation and availability in soils. They can occur within the boundaries of a tubewell command area.

1.3.2 Soil Accumulation

Little of the arsenic added to soils in irrigation water is lost by leaching or removal in crops. Arsenic therefore gradually accumulates in topsoils with time.

1.3.3 Variations within Tubewell Sites

The extent of arsenic-affected soils is not yet known. Assessment is made difficult by differences between tubewells in the arsenic concentration of the water they deliver, the length of time that soils have been irrigated and rates of accumulation within command areas. Not all the arsenic delivered by tubewells reaches the fields irrigated. As the water becomes aerated in passing along irrigation channels and over fields, ferrous iron in the groundwater changes to the ferric (rust) form, which adsors some of the arsenic. Hossain (2005) reported that arsenic concentrations in the water at a 4-ha tubewell site near Faridpur, Bangladesh, fell from 136 ppm at the well-head to 68 ppm at the end of the 100 m distribution channel. Topsoil arsenic concentrations at this site, which had been irrigated for 15 years, ranged from 61 parts per million (ppm) in the field nearest the well to 11 ppm in a field at the far side of the command area. At another site that had been irrigated for 20 years, Dittmar et al (2007) reported that topsoil arsenic concentrations varied considerably within fields: for example, from 23 ppm near the irrigation inlet in one field to 11.3 ppm at the far side of the field. Such differences within command areas and within individual fields will increase with time as irrigation continues. These differences need to be taken into account in soil and crop studies. They will also need to be considered in planning mitigation measures because soils in fields nearest a well will become severely contaminated before those in outer parts of the command area.

1.3.4 Laboratory Analysis of Soil Arsenic

Conventional methods of soil analysis are poorly suited for use on paddy soils. There is little correlation between the amounts of arsenic (usually “total”) determined in the laboratory and the amount that is actually available to rice plants growing in reduced and anaerobic soils. Methods need to be developed and introduced that will give more relevant results. Attempts are also needed to develop a quick, indicative method that could be used to determine soil arsenic concentrations in the field. The use of such a method would enable large numbers of samples to be tested, tested more cheaply and results provided for immediate use instead of after a delay of several weeks.

1.4 Arsenic in Plants

1.4.1 Availability to Plants

Rice is the crop that is most affected by arsenic uptake. That is because it is generally grown in flooded fields in which the topsoil is anaerobic and strongly reduced, the condition under which arsenic is most readily available to plant roots. Also, much more water is used to irrigate rice than is used on dryland crops. Dryland crops such as maize, wheat and vegetables grown on dryland soils take up much less arsenic because arsenic in irrigation water is quickly immobilised by iron-hydroxides in aerated soils.

1.4.2 Tolerance and Toxicity

Different plant species tolerate different amounts of arsenic in soils. Even different rice cultivars differ in arsenic tolerance. An arsenic-related disease known as “straighthead” (so-called because of upright, empty panicles at maturity) or “parrot beak” (because of misshaped grains)
was reported for the first time in Bangla-
desh in 2006 [Duxbury and Panaullah
2007]. Yan et al (2005) found virtually
no yield reduction in one Chinese rice
cultivar but up to 80-90 per cent reduc-
tion in four of 10 US cultivars tested on
high-arsenic soils in the US. In Bangla-
desh, Duxbury and Panaullah (2007) re-
ported yields of a single rice variety
(9829) decreasing from 8.9 tonnes/ha at 26.3
ppm soil arsenic to 3 tonnes/ha at 57.5
ppm arsenic. Their results suggest that
the practical limit for paddy cultivation might
lie somewhere between 25 and 50 mg/kg
soil arsenic. However, differences in
varietal tolerance described above need to
be kept in view. So do differences in the
amounts of arsenic transferred to rice
grain (described below). Safe levels of soil
arsenic for dryland crops that are grown
with irrigation remain to be determined.

1.4.3 Plant Uptake
Arsenic taken up from soils by rice accumu-
lates in different proportions in differ-
ent plant parts in the order roots >stem
>leaf >grain [Abedin et al 2002]. In pot
found 2.4 mg/kg arsenic in rice roots, 0.73
mg/kg in stems and leaves, and 0.14 mg/
kg in grain. However, there are considera-
dible differences in uptake between rice
varieties and between the kinds of rice grown
in different countries. Meharg and Rahman
(2003) found grain arsenic contents rang-
ing between 0.058 and 1.835 mg/kg in 13
different rice varieties tested in Bangla-
desh and 0.063-0.2 mg/kg in Taiwan.
Duxbury and Zavala (2005) reported lower
mean concentrations, 0.032–0.046 mg/kg
arsenic, for aromatic rices from Bangla-
desh, Bhutan, India and Pakistan.

Duxbury and Panaullah (2007) found
that significant amounts of arsenic were
taken up by rice grain even at low soil ar-
senic concentrations: 0.54 mg/kg in grain
at 11.6 ppm soil arsenic versus 0.35 mg/kg
at 57.5 ppm soil arsenic (where yields were
much lower). These results were obtained
in a field trial; even higher grain concen-
trations were obtained in pot trials with
samples taken from the same soils. These
findings suggest that dangerous amounts of
arsenic might be taken up by rice at
soil arsenic levels below those when rice
yields begin to be affected. However, it is
dangerous to generalise from a single
trial. Therefore, this trial needs to be
repeated over a wider range of soils and
rice varieties to obtain results that could
provide the basis for sound recommenda-
tions to farmers and also a basis for
assessment surveys.

The differences between rice types and
cultivars need to be taken into account in
assessing the dietary intake of arsenic by
people living in arsenic-affected areas.
Since relatively large amounts of arsenic
are taken up by rice stems and leaves,
potential health effects on livestock eating
contaminated rice straw also need to be
examined, and so do the quality of meat
and milk products from such livestock.
The trials reported by Duxbury and Pan-
aullah (ibid) showed that arsenic in rice
straw increased with increasing soil
arsenic concentrations.

1.5 Human Impact

1.5.1 Dietary Implications
The arsenic content of rice grain is impor-
tant because of the large amounts of rice
eaten by people in many parts of India,
Bangladesh and Nepal (an assumed 450 g/
day for a 60 kg adult in Bangladesh). When
arsenic in rice grains is 0.2 mg/kg, adults
consuming 450 g of rice and 4 litres of
water per day at the 10 ppb WHO water
standard consume 130 µg of arsenic per
day, which is the FAO and WHO tolerable
dietary intake standard for a 60 g
adult; (persons consuming 4 litres of water
at 50 ppb national standards already
exceed that level before eating any rice).
Uchino et al (2006), who measured
arsenic contents of hair and urine samples
from members of 37 families in West
Bengal villages with respectively <10,
10–50 and >50 ppb arsenic in drinking
water, found that total daily arsenic intake
of adults from water and food (rice + veget-
tables) was approximately 1.5, 2.7 and 6.1
times the FAO-WHO standard in villages in
the respective low, moderate and high
drinking water classes. Food was the main
source of arsenic in families drinking
water in the two lower classes.

1.5.2 Health Impacts
In effect, there is no safe level of arsenic
intake from food or water. There is a linear

dose-response relationship between ar-
senic intake and health hazards down to
very low levels of intake. Arsenic causes
serious skin lesions and various forms of
cancer and it can cause deaths from a
wide range of other serious diseases
[Meharg 2005]. Symptoms may not appear
for two to 10 years from the start of chronic
exposure and they may also appear long
after exposure ceases. Therefore, efforts
need to be made to minimise arsenic in-
take from all sources as soon as possible.

1.5.3 Social Impact
Poor families and women are particularly
affected by the health impacts of chronic
arsenic consumption [Sultana 2007]. Sick
family members may be unable to work or
to obtain adequate medical treatment.
Women with disfiguring skin lesions may
be denied marriage or be divorced.

2 Mitigation Measures
Most studies on the reclamation of arsenic-
contaminated soil have been carried out
on sites contaminated with mining, indus-
trial or urban wastes or on soils contami-
nated with arsenical pesticides. Few of
these methods appear to be suitable for
small-scale rice farmers. Mitigation
methods appropriate for paddy soils need
to be identified, tested and propagated as
soon as possible in areas where arsenic
pollution of soils and crops is found to
be serious or imminent. Methods that
might be practical will vary from place to
place according to soil, climate, flooding
and socio-economic conditions. Different
methods might even be required within
the boundaries of individual tubewell
command areas. The possible methods
that might be appropriate are listed in the
table (p 82) and are described below.

2.1 Surveys
The most urgent need is to assess the scale
of the soil-arsenic contamination problem:
which areas are already affected; and
which areas might be affected in five to 10
years’ time if present rates of soil-arsenic
accumulation continue. An indicative pic-
ture could be obtained by superimposing
a map showing the areas where drinking-
water tubewells are known to be arsenic-
contaminated on a map showing the areas
where groundwater is used to irrigate rice.
Field surveys could then be organised to collect specific information on the number and location of irrigation tubewells delivering high arsenic levels in water, the number of years that they have been in use and soil arsenic contents.

At tubewell sites where irrigation with high-arsenic water has been practised for many years, topsoil samples should be taken from fields at different distances from the tubewell and from the water intake in selected fields. That would provide a preliminary indication of the extent of soils within command areas that presently have >25 mg/kg and >50 mg/kg arsenic, or might reach those levels within the next five to 10 years at present rates of arsenic accumulation. (Arsenic levels in uncontaminated soils are generally <10 ppm, and often <5 ppm.) Such surveys could initially be done on a sample basis to provide a rapid indication of any actual or potential threat to agricultural production and human health, then followed by a full-scale survey in areas found to be most at risk. In this way, the scale of actual or looming threats from soil-arsenic accumulation could be obtained to form the basis for planning relevant research and mitigation programmes.

### 2.2 Water Treatment

It is considered impractical to provide water-treatment methods used for drinking water to treat the enormous quantities of irrigation water used (especially for rice) because of the cost. However, the natural co-precipitation of arsenic with ferric iron that occurs in irrigation distribution channels provides a simple and practical means to reduce the amount of arsenic reaching fields. Methods to enhance this process need to be tested: for example, by increasing turbulent flow and aeration in distribution channels; providing field or overhead settling tanks; and possibly by adding ferric iron material in settling tanks or channels. In all cases, practical methods will need to be tested for periodically removing the arsenic-enriched material and disposing of it safely so that it does not create another health hazard.

### 2.3 Alternative Irrigation Supply

The best way to limit the threat of soil arsenic contamination is to stop adding arsenic to soils. Therefore, alternative safe sources of irrigation water should be sought and provided as soon as possible wherever that is practical. Possibilities will vary from area to area: surface water supplies from rivers or reservoirs; or use of safe deeper aquifers. Such alternative water sources will probably be more costly to provide, operate and maintain than existing shallow tubewells and subsidies may need to be considered. The costs of subsidies should be weighed against the increasing health, social and economic costs of continuing irrigation with contaminated water until soils and crops become highly contaminated, crop yields and production fall to uneconomic levels, and more people need medical treatment.

It will not be possible to provide safe irrigation supplies in all areas. Even where such possibilities exist, it may take several years before they can be provided. Therefore, in many areas, the next best alternative will be to reduce the rate of soil arsenic accumulation. Those methods are described below.

### 2.4 Agronomic Methods

#### 2.4.1 Dryland Crops

Substituting dryland crops such as maize or wheat for rice in appropriate climates could reduce the rate of arsenic accumulation in soils and food crops. So could the substitution of appropriate vegetables and cash crops. Dryland crops use much less water than paddy rice, so correspondingly less arsenic is added to soils. Arsenic is also more rapidly immobilised by ferric iron in dryland soils, so less is taken up by crops. However, rice is by far the preferred crop option for farmers in most arsenic-affected areas of India, Bangladesh and Nepal, so it would need to be ensured that the economic returns from substituted dryland crops at least match those from paddy cultivation, including the costs to families of buying the rice they may no longer grow. Much of the land currently irrigated is better suited to paddy rice than to dryland crops and drastic alterations to land and soils might be needed in some places to enable dryland crops to be grown reliably, as is described below.

#### 2.4.2 Raised Beds

On floodplain land, dryland crops are likely to be a better option on relatively better-drained ridge soils which generally are lighter-textured and more permeable than are poorly-drained, heavier, basin soils. Rice can be grown as a dryland crop on relatively well drained soils. On relatively lower sites and heavier soils, it would be necessary to form raised beds on which to grow rice as a dryland crop. On heavy basin clays, beds would need to be made high enough to ensure satisfactory drainage during heavy rainfall and at the beginning of monsoon-season flooding. The practical limits for constructing and maintaining such beds need to be determined in field trials. Studies have recently been initiated in Bangladesh to test rice cultivation on raised beds, with initially beneficial results on rice yields [Duxbury and Panaullah 2007]. However, more years of study are needed to test farmer acceptability and monitor conditions to see if any problems arise. The method also needs to be tested under a wide range of soil and climatic conditions. Because of the drastic change to soil properties involved in making raised beds on basin clays, initial trials would best be made on research stations rather than on farmers’ fields.

#### 2.4.3 System of Rice Intensification

The system of rice intensification (SRI), which is being promoted in several countries in Asia and Africa appears to be well adapted to growing rice as an irrigated dryland crop. In this system, single rice seedlings eight to 15 days old are transplanted...
very shallowly at 25 × 25 cm (or wider) spacing. This results in many more tillers (stems) being formed than with conventional transplanting practice, which helps to shade out weeds and increase yields [Stoop et al 2002]. This system deserves testing in arsenic-affected areas to find out the range of environmental conditions under which it might be suitable.

### 2.4.4 Arsenic-Tolerant Varieties

Research is in progress to breed arsenic-tolerant rice varieties. However, it needs to be borne in mind that the use of tolerant varieties does not reduce the rate of soil-arsenic accumulation. Therefore, as with the other agronomic practices described above, irrigation with contaminated water will continue to add arsenic to soils, albeit at a slower rate where dryland crops or dryland rice are grown. The real need is to prevent further additions of arsenic to soils, especially to soils where arsenic levels are already high.

### 2.4.5 Drainage

Allowing rice fields to dry out completely for 10-14 days prior to panicle initiation is practised to reduce arsenic uptake in the southern US but this also reduces potential rice yields [Williams 2003]. This practice may not be acceptable to small farmers, therefore. It would also not be applicable to rice grown on seasonally-flooded soils in rotation with a dry-season crop irrigated with arsenic-contaminated water.

### 2.4.6 Rainfed Agriculture

In areas where an alternative safe irrigation supply cannot be provided, farmers should be encouraged to increase crop production under rainfed conditions. The possibilities will vary with climate, soils and hydrological conditions. Research studies and field trials should aim to maximise soil absorption and retention of rainfall and run-off by appropriate conservation and agronomic measures. Methods such as the SRI described above and minimum-tillage farming [FAO 2005] deserve study under appropriate environmental conditions.

### 2.5 Soil Amendments

#### 2.5.1 Iron

Ferric iron in various forms has been used in developed countries to immobilise arsenic on dryland soils. Materials used include ferrous sulphate and iron grit. In Asian countries, it might be possible to use crushed brick or burnt soil for the same purpose. However, it needs to be investigated whether such materials would be effective in flood-irrigated soils in which the iron would eventually be reduced; and also whether the adsorbed arsenic would be remobilised to affect a following rice crop on seasonally-flooded soils.

#### 2.5.2 Phosphorus

The potential benefits of adding phos- phatic fertilisers to reduce arsenic uptake by crops also deserve testing under a range of soil and agronomic conditions. Conflicting results have been reported from pot trials. In principle, arsenic (present as arsenite) in reduced soils should not compete with phosphorus. Therefore, adding phosphate to paddy soils should not influence arsenic uptake by crops. However, the situation is different in oxidised soils where phosphorus and arsenic (as arsenate) compete for uptake sites on plant roots and so plant uptake of arsenic might be reduced where large amounts of phosphorus are added. The situation is complicated by the fact that arsenate and phosphorus also compete for adsorption by ferric iron, so the content of iron in soils (including that precipitated from high-iron irrigation water) may also influence the effect of added phosphorus on arsenic uptake. Pot trials need to be supplemented by field trials on reduced and oxidised soils as soon as possible.

### 2.6 Soil Rehabilitation

When soil arsenic concentrations reach levels where crop yields are seriously reduced or arsenic uptake by rice exceeds dietary safety standards, methods to remove arsenic from soils will need to be adopted. The only practical methods known at present are described below.

#### 2.6.1 Hyperaccumulator Plants

Some plants have the ability to take up very large amounts of arsenic from soils. In pot trials in the US, Ma et al (2001) found that the fronds of brake fern (pteris vittata) growing in soil material containing 6 mg/kg arsenic had accumulated 755 ppm arsenic after two weeks and 438 ppm after six weeks. At 50 mg/kg soil arsenic, they found 5,131 ppm arsenic in fronds at two weeks and 3,215 ppm after six weeks. Information was not provided on the biomass produced after these periods. Assuming production of 10 tonnes/ha, fern fronds containing 3,215 ppm arsenic could remove 32 kg/ha arsenic from soil. That is equivalent to several years' input of arsenic from contaminated irrigation water.

Brake fern could probably only be grown under dryland conditions. Trials are needed to see if this fern could be grown as a short-term crop in the dry season before an irrigated rice crop is planted. Several other fern species are also reported to be hyperaccumulators [Wei et al 2005], and so is Indian mustard [Mahimairaja et al 2005]. Water hyacinth (eichhornia crassipes) is also a hyperaccumulator but this plant grows in water, so its use might be to remove arsenic in settling tanks before water is distributed to fields. This possible use needs to be investigated.

All these plants need to be tested to assess the range of environmental conditions under which they could be grown and their ability to remove arsenic from soils in meaningful quantities. At the same time, practical methods will need to be found for the safe disposal of the large quantities of arsenic-enriched plant material produced and to assess the health risk to people (especially children), livestock and wildlife eating the plants or inhaling dust from burnt material.

#### 2.6.2 Soil Removal

As a last resort, it might be necessary to remove soil material that has become too heavily contaminated with arsenic to produce satisfactory crop yields or rice of satisfactory quality. Fortunately, it is only the topsoil that becomes heavily contaminated, so only 10-15 cm of soil material would usually need to be removed. Soil removal is not as drastic a remedy as it may seem. In Bangladesh, farmers commonly sell soil material for brick-making and soil material is commonly removed from fields for making footpaths and embankments. After soil removal, farmers add farmyard manure, compost or dry
water hyacinth plants to restore soil fertility and tilth; they also grow jute and deep-rooting legumes to help restore soil tilth.

In fields where soils are already heavily contaminated, topsoil removal might be the quickest and simplest method to restore crop production to acceptable levels. Trials are needed to find the most appropriate methods for restoring soil fertility after topsoil removal and for safe use of soil material removed. Where rice is the preferred crop, particular care would need to be taken where topsoil removal might bring a permeable lower layer close to the surface and so lead to excessive irrigation demand and attendant risks of increased arsenic contamination.

Conclusions

Irrigation with arsenic-polluted groundwater poses a threat to sustainable agriculture and health in several parts of India, Bangladesh and Nepal. The scale of that threat is presently unknown. It urgently needs to be assessed, so that appropriate research studies and interventions can be organised. Ongoing soil and crop research studies (mainly in Bangladesh) are providing valuable results but they are far too few to provide the information needed for planning reliable interventions in the wide range of environments that exist in affected areas. The development of a quick, reasonably reliable, field method for testing soil arsenic would greatly facilitate the assessment and monitoring of soil arsenic levels and methods of laboratory analysis need to be developed that are better adapted to paddy soils. Field trials need to be used much more extensively because it is practically impossible to simulate the physical, chemical and biological environment of a paddy soil in a pot experiment. Trials with possible mitigation measures need to be organised, taking into account the time that will likely be required to provide applicable results. In badly-affected areas, agricultural research, soil survey, soil laboratory, extension and possibly engineering institutions may need strengthening or reorganisation in order to provide appropriate services to affected farmers. Governments, international aid donors and NGOs should consider these increased or changing needs in reviewing their development programmes in affected areas.

REFERENCES


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