J. ENVIRONMENTAL SYSTEMS, Vol. 32(4) 335-348, 2005-2006

ENVIRONMENTAL SYSTEMS COLLAPSE: A QUALITATIVE CRITIQUE WITH AN EXEMPLAR

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ABSTRACT

Groundwater systems alarmingly contaminated with arsenic content have become a matter of great concern in India and many other nations presents a broad assessment of this problem and connects it to non-linearities potentially leading to chaotic collapse. A systems approach provides enabling techniques for anticipating the collapse of the system. The use of mathematical models facilitates the unfolding of the dynamics involved. A qualitative consideration exemplars in the Bengal basin of India reinforces the conclusions and prognoses that are well in accord those in the 2006 Living Planet Report from the prognostic viewpoint.

The word "arsenic," generally associated with the poisonous attributes of a material, has, of late, posed serious problems requiring efforts to contend with uncertainties regarding its health impact even at low concentrations. Few agencies seek to set a "maximum contaminant level goal" at zero for drinking water. The Bengal basin has likewise posed major hazards because of the arsenic concentration in the shallow, reducing groundwater environment. These are found to be aquifers with high concentration of arsenic (Nath, Chakraborty, Burnol, Stuben, Chatterjee, & Charlet, 2009; Pal, Mukherjee, & Sengupta, 2002). Although Pal and colleague's (2002) analyses tell that there is no interflow between the aquifers, it is the anaerobic microbial respiration regime that keeps

doi: 10.2190/ES.32.4.d
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accumulating the arsenic from the host minerals, especially oxides of iron, and concretionary growth of iron carbonates, layered phyllosilicates and clay minerates (Mukherjee-Goswami, Nath, Jana, Sahu, Sarkar, Jacks, et al., 2008; Pal et al., 2002). It is relevant to bring out here that even if there is a flow between two aquifers and the groundwater has a microbial content, the flow tends to become turbulent creating a different and complex mathematical problems. The investigations presented here bring out the role of the human activity in exacerbating the release of arsenic in groundwater. This calls for an effective remediation system which should investigate the possibility of limiting arsenic concentration in the shallow aquifer systems.

The layout of this article is as follows. The problem is formulated with some hypotheses about the dynamics of arsenic release to the groundwater regime. A theoretical modeling is then attempted, and global implications are drawn. The results are then analyzed. A few exemplars in some local milieus are taken up. The article winds up with conclusions applicable largely to the regions dealt with in the article.

PROBLEM AND ITS FORMULATION

Let us begin with a few hypotheses to formulate the problem more sharply. First, when the water table becomes shallow, excessive drawing of water from the surface results in oxygen intrusion which causes the oxidation of the arsenic-rich host sediments to release arsenic in the surrounding water body. This process is controlled by the chemical composition of the sediments as well as the pH condition of the local in-situ environment.

Second, the phosphate sources from the irrigated fields that remain adsorbed cause desorption of arsenic in the water, depending on relevant parameters. In this case, the important input parameter is the mass of sorbent material present between the aquifer and the paddy field which receives the primary phosphate compounds.

The third hypothesis concerns the microbial reduction of hydrous iron oxides (in the sediments) which allow the material from the surface to seep through to the lower layers. The most important parameter here is the rate of the relevant reactions.

THEORIZATION: A PRELUDE TO MODELING

If our purpose is to limit the concentration of the soluble arsenic in the aquifer, then we should seek a model where $X(t_n)$, the concentration of As at a particular time, say t_n, is non-linearly related with value of X at a subsequent time t_{n+1}.

$$X(T_n) = F(X(t_{n+1}))$$

Furthermore, this relationship must have a certain specific geometrical characteristic. The functional form of F(X), intuitively, should have a parabolic form such that the intersection of the graph F(X) and the graph Y = X leads to the destination of a fixed point P. The fixed point P is defined as a point (in journey of The function F in the time domain t) when the nth value of F equals the (n + 1)th value after the journey of some finite time range.

This can be demonstrated by the simple standard example as shown in Figure 1.

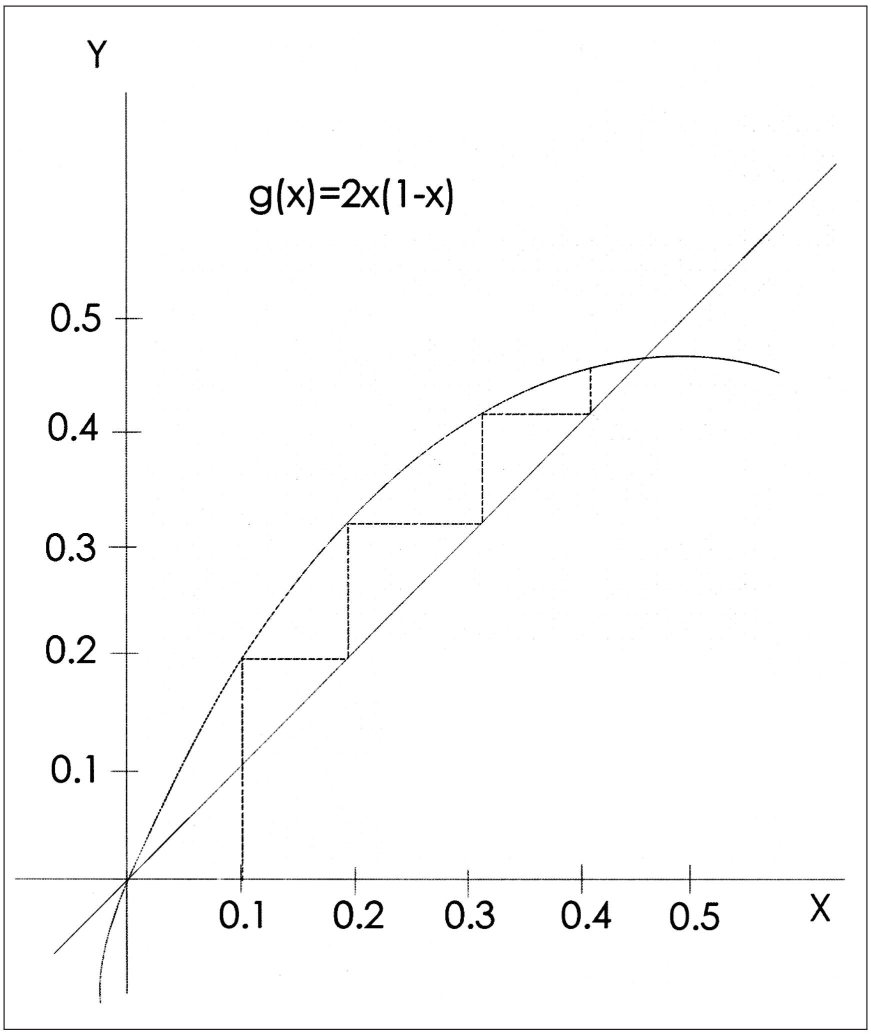

Figure 1. A cobweb plot for an orbit g(x) = 2x (1-x).
The orbit with initial value 0.1 converges to the sink at 0.5.

In this example, where $F(X) = 2X(1-X)$, there is a fixed point P at $X = 0.5$ (Figure 1).

Let us try to seek this type of model for the case of Arsenic concentration X in The groundwater.

Assume Y = concentration of As-enriched sediment in the soil below the aquifer.

P = the rate of chemical reaction (of any kind) that transfers As from the host sediments to the aquifer. Then

$$X(t_{n+1}) = Y^* (P(t_n)$$

If there are biological inputs as well, say, B, we shall add another term

$$X(t_{n+1}) = Y^* P(t_n) + B(t_n)^* P(t_n)$$

However, the amount of As in the aquifer plus the amount in the sediment should be constant, i.e.,

$$X + P = \text{constant} = A \text{ (say)}$$

In other words,

$$P(t_n) = A - X(t_n)$$

Therefore,

$$X(t_{n+1}) = (Y + B(t_n))^*(A - X(t_n))$$

Clearly, the cobweb plot is of quasi-linear nature. Therefore, we cannot expect to arrive at a fixed point.

On the other hand, if the reaction Y is dependent on the prevailing pH factor which, in turn, depends on the amount of As released in the water, then one can hope to arrive at a non-linear relationship, leading to a possible fixed point.

We can thus express:

$$(1 + C)^n = K(t). (1 + x)^n. (1 + y)^n. (1 + z)^n$$

where:

K > 1 (unless any improvement by intervention in ground condition takes place),
n = number of years = (t)
C = (natural) collapse
$(1 + C)^n$ = rate of increase of collapse repeating with a time lag when The population crosses the threshold of ecological footprint.
$\{(1 + X)^n\}$ = rate of increase in the population in the n number of years resulting in increase of rate of water extraction, i.e., $\{(1 + y)^n\}$; the growth rate of organisms $\{(1 + z)^n\}$ also enhances. Here x, y, z are all taken to be man-made.

The arsenic distribution pattern, a natural phenomenon, indicated by the Baruipur block reflects a bifurcation (Figure 2) suggesting a signature of chaos (Gleick, 1987).

SYSTEMIC VIEW

As we are trying to look at the problem from a systemic angle, our objective is to evaluate the systems impact and the resultant output arising out of the collision of the three dynamic systems involved—population growth (human resource growth), agricultural state, and shallow aquifer behavior, giving rise to phenomenological observations.

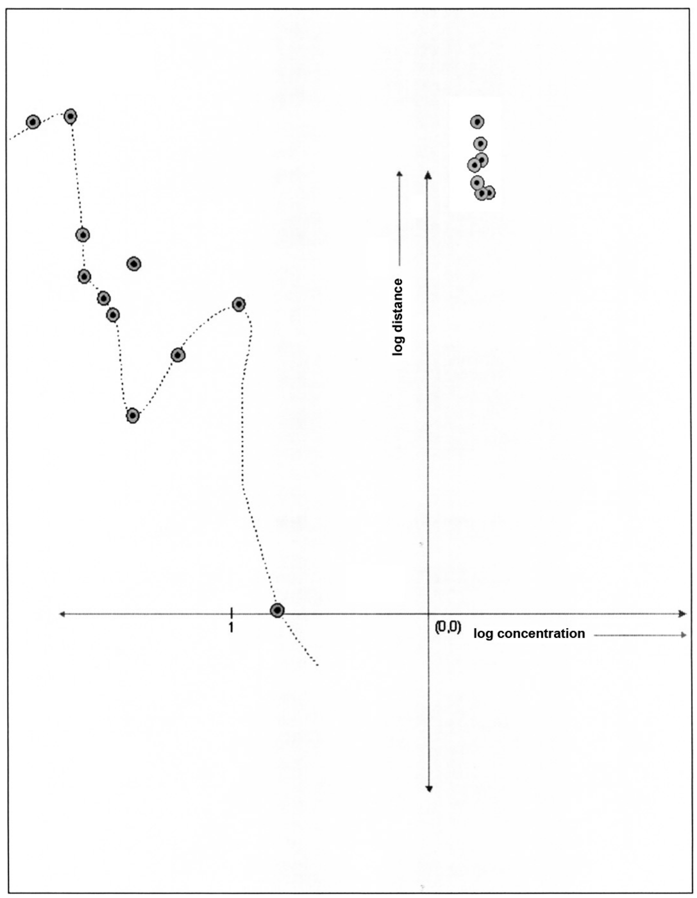

Figure 2. Arsenic distribution pattern in Baruipur block reflects a bifurcation suggesting a signature of chaos.

The Living Planet Report - WWF - India 2006 hinted at the increasing possibilities of large scale ecosystem collapse arising out of the ecological deficit and exhaustion of ecological assets, resorting to solutions which shift demand from one ecosystem to another. The context discussed is the "Business-As-Usual Scenario."

In this backdrop, the present research investigated the Baruipur Block, South 24 Parganas (situated to the south of Calcutta, covering an area of 212.48 sq. km with a population of 351,569 as per the 2001 Census) with a density of population greater than 1,650 persons/sq. km. The block is thickly populated as, especially after the partition of Bengal, the population went up rapidly with the migration of refugees to 24 Parganas, West Bengal, India (a part of the Bengal basin). The predominance of arsenic in groundwater is a known acute phenomena since the 1970s; in fact, the first report (Report of Govt. of West Bengal) of arsenic poisoning in West Bengal came from this particular block. The area as a consequence suffers (Source: Govt. of West Bengal Reports) from a severe shortage of potable drinking water. The Ramnagar area in the eastern part of this block has the first reported death due to arsenic contamination.

The various signatures developed, shown by arsenic contamination patterns in the aquifers in the Bengal basin, depict changes in the system's behavior. These features indicate the possibilities of discontinuities in the sequence of events. We should of course proceed to look for polymorphic causes and delayed temporal impacts on the systems with manifold ground effects leading to the environmental systems collapse in the region—a normal response behavior of ecosystems.

GLOBAL/REGIONAL IMPLICATIONS HIGHLIGHTING THE THREAT OF COLLAPSE OF THE NATURAL SYSTEM: REALITIES IN THE ASIAN RIVER SYSTEMS

The world is aware that the 21 Asian rivers are facing imminent collapse of their total systems. The river Huang Ho, the yellow river in China, is already dead. The Ganges and the Indus in the Indian subcontinent, the Yangtze in China, the Mekong in Vietnam, the Salween in Burma, and the Euphrates-Tigris in Iraq are having a hard time surviving as normal functional river systems. They are in distress because of human interference—man-made pollution. Most of the sewage and industrial waste in China flows into the Yangtze. The raw toxic effluent—up to a billion litres from the leather processing industries at Kanpur, located on the bank of the Ganges, alone—is directly diverted into the river. China's interventions in the Upper Mekong are having deleterious consequences downstream—navigating is becoming difficult for the fishermen and fish are becoming scarce for the Laotian fishing dwellers. The Yangtze dolphins are already extinct while the Indus dolphins have been physiologically affected by pollution. Things are not promising for the dolphins of the Ganges. They are endangered species—all because of man-made water pollution. In Thailand, because of the deteriorating condition of the Mekong river, the flood pattern is disturbed, and the Cambodian "Tonle Sap" lake is inching toward extinction because of water shortages generated by tapping of water by China in the upper reaches. In Vietnam, the problem is reflected in the delta region where salinity has reached an abnormally high level. If such a situation persists, there will be a total collapse of the riverine ecological system in Vietnam and the surroundings.

ANALYSIS

Analyzing the shallow groundwater arsenic contamination status in West Bengal, we find that the western districts of West Bengal like Midnapur, Bankura, Purulia, and Birbhum have less than 3 ppb of arsenic in their aquifers (Figure 3). Dinajpur and Cooch Bihar districts indicate between 3-10 ppb. The data confirm that in the western part of West Bengal, the intrinsic characteristics of the aquifers are independent of scale (Mandelbrot, 1982). In the smaller scales of Dinajpur and Coach Bihar too, the arsenic trend reflects an invariant characteristic. Such an invariant behavior of arsenic in the shallow aquifers of the aforesaid districts, being independent of scale, suggests that in the Bengal basin this could be the initial condition of the shallow aquifers, not much disturbed at all. Arsenic was hence no factor to be mentioned in these districts/regions during the exploration of groundwater in the 1950s. Such a scenario, perhaps, depicts the original ecological system to be still persistent in the region. It can thus be logically assumed that the remaining eastern part of West Bengal must have been a part of the original natural system. But as time passed, with a sudden population increase, (hence) over-extraction of groundwater and the adequate availability of microbiological mass-mediated reductive dissolution of arsenic-rich hydrous iron oxides with production of bicarbonate might have further exacerbated the arsenic release (Mukherjee-Goswami et al., 2009; Pal et al., 2002). The original/initial eco-environmental system in the eastern sector by the River Ganges collapsed in a constantly changing and unpredictable natural environment; inconsistencies within the system will inevitably give rise to such a conflict situation. In such a scenario, sudden changes in chaotic attractors are plausible (Grebogi, Lott, & Yorke, 1983).

Systems collapse here may define multiple failure modes. Unlike cancer (which is a single collapse), any local failure in the natural/environmental systems results in another failure, which may repeat, and finally lead to failure of events.

For example, in local milieus, the shallow aquifer system in the Bengal basin of West Bengal and in the majority of the districts along the Ganges, has collapsed in the context of the arsenic contamination. The collapse scenario as comprehended is depicted in Figure 4. And the collapse has been both spatially and temporally triggered by three factors—the growth of population with sudden spurts, over-extraction of groundwater for drinking purposes and agriculture, and the availability of reductive microbe assemblages.

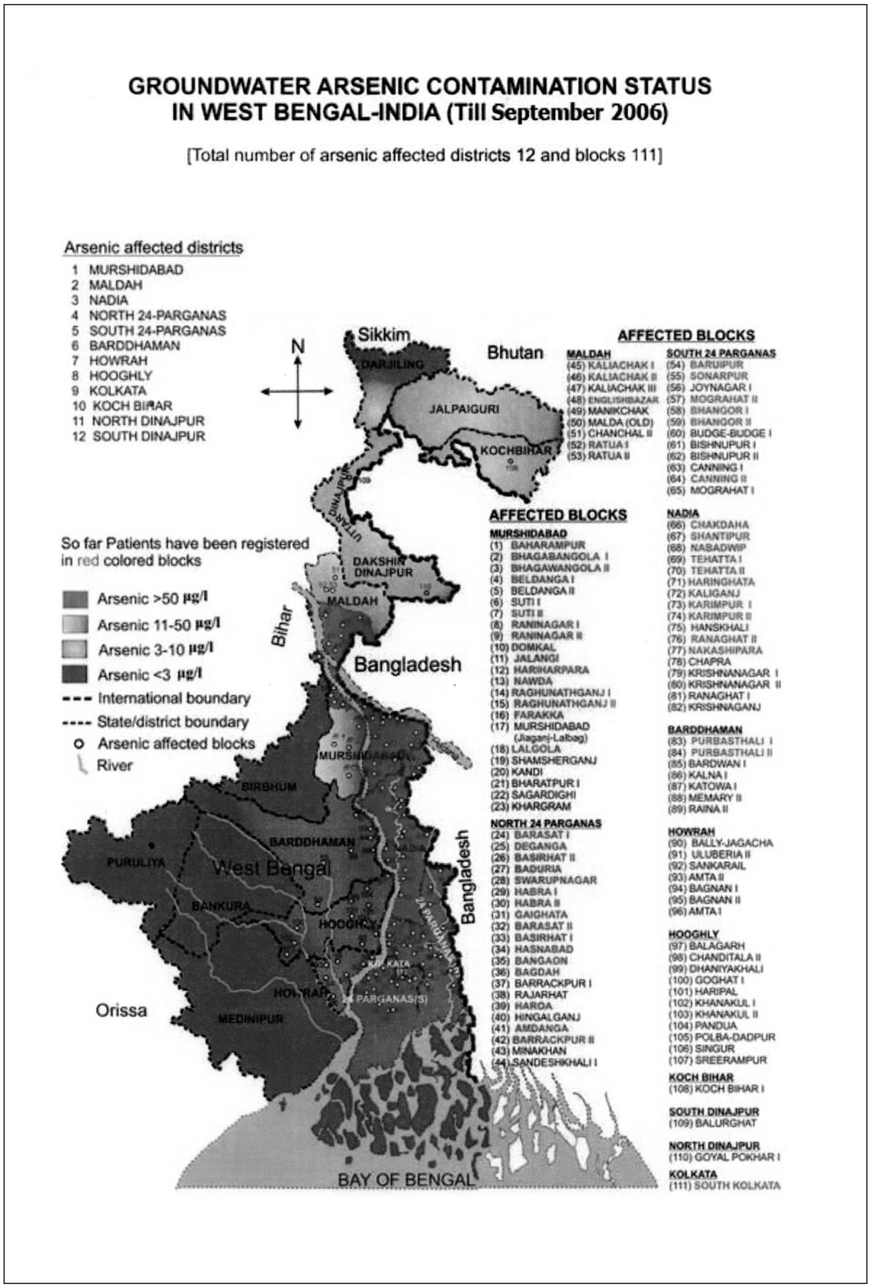

Figure 3. Groundwater arsenic contamination status in West Bengal - India.
Source: School of Environmental Studies, Jadavpur University.

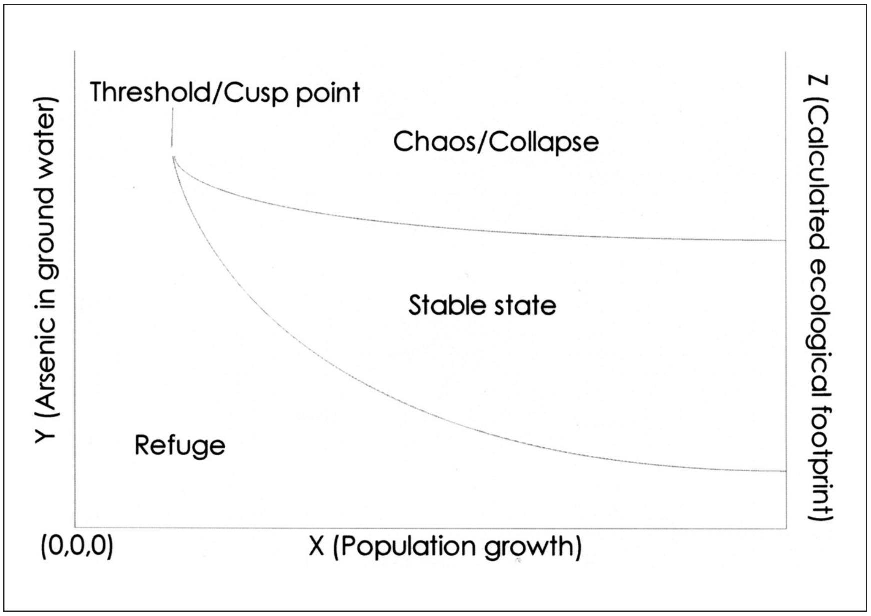

Figure 4. The collapse scenario predicted in terms of ground realities.

REDEFINING THE MODELING

As the system collapsed in the Bengal basin where the population increased at the rate of 30%-40% in 10 years (overall population of West Bengal increased by 18.4% during the same period), and so did the amount of groundwater over-extraction [much more than the aquifers could sustain—that is the case with Ramnagar in Baruipur block, South 24 Parganas district, where a shallow "well" often dries up and shows a very high concentration of arsenic (3.0 ppm)]. The system in the eastern districts of West Bengal collapsed and changed to another system, where the base/background level of arsenic content was much different (in the groundwater) as compared to the western districts where population increase and water extraction appeared to be ecologically sustainable. Any natural/environmental system always tries to compensate for the failure in its own way. We know that systems use "resilience" mechanisms to maintain stability in the face of environmental/ecological changes; in the management science too, when systems break down, one has to compensate to get the results. Stretching the system continuously initiates renormalization to sustain stability. It reflects the endless repetition of the same dynamical processes; a 2^n cycle is born, then becomes superstable and then loses stability in a period—doubling bifurcation (Alligood, Sarcer, & Yorke, 1996).

The relevance of renormalization creeps in because we are considering an ecosystem collapse. At the level of ecological deficit and exhaustion of ecological assets (because of uncontrollable growth of population), ecosystem collapse can take place. Mandelbrot (1977) has argued that a wide range of natural objects and phenomena are fractals; examples include fractal trees, river systems, cauliflowers, and the cardiovascular systems. The renormalization group approach is applicable to the collapse of fractal trees, problems of instability as in earthquake and in the overshooting of ecological footprints.

This is a scenario similar to the business-as-usual scenario based on the UN projections of steady growth of economies and populations. In this case, however, the population growth is exponential. Renormalization reflects, on the basis of self-similarity of the fig-tree (*Ficus carica*) (since chaos and ultimate collapse occurs because of self-similar repetitions of act in Baruipur), endless repetition of the same dynamical processes—a 2^n cycle is born, then becomes super-stable and then loses stability in a period doubling bifurcation (Alligood et al., 1996). It is probably a case of universal function [$g_o x$] which means that the limiting function is independent of the original (f). After renormalization "n" times, we get as in our case of collapse.

$$f(x, R_0) = \alpha^n f^{(2^n)}\left(\frac{x}{\alpha^n}, R_n\right)$$

$$\lim_{n\to\infty} \alpha^n f(2^n)\left(\frac{x}{\alpha^n}, R_n\right)$$

To obtain $g_i(x)$, the other function, we start with f (x, R_i) instead of f (x, R_0):

$$g_i^x \cdot \lim_{n\to\infty} \alpha^n \cdot f^{(2^n)} \cdot \left(\frac{x}{\alpha^n}, R_{n+i}\right)$$

where g_i (x) is a universal function with superstable 2^n cycle. The case where we start with $R_i = R_a$ (at the outset of chaos) is most interesting.

Since then,

$$f(x, R_\alpha) = \alpha \cdot f^2 \cdot \left(\frac{x}{\alpha^n}, R_\alpha\right),$$

here the limiting function g_i (x), called g(x) satisfies

$$g(x) = \alpha g^2\left(\frac{x}{\alpha}\right)$$

g(x) is here defined in terms of itself.

Since the boundary conditions of the ecological subsystems in the present environment are in a continuously changing mode, the same could not be specified; hence the functional equation may pose difficulties.

It is further noted that the cluster of values with no discernible patterns in the Ramnagar-Sarkarpara area also indicates chaos. There is perhaps a non-linear chaotic system prevailing in the arsenic-rich blocks in the eastern districts of West Bengal in the Bengal basin. But the western districts expose a contradictory situation.

As mentioned earlier, a non-linear chaotic system by its nature itself cannot continue to be stable for a long time. They tend to change expressing an unpredictable behavior of deterministic non-linear dynamical system. If the population increases at a higher rate as is likely, or even at the same rate (30-40% in 10 years), the water extraction rate will rise exponentially and there will again be a systems collapse, and probably a second one in another 10 years or so, with a resultant higher arsenic base/background level in the aquifers. The system is iterative as the population is continuing to increase.

In the perspective of the present state of arsenic pollution of groundwater in West Bengal, a correct decision with interventions either in population growth or in groundwater use or in land use in expansive agriculture is necessary. The present workers tend to conclude that an assessment of ecological footprint throughout the state, particularly in the affected districts, has become imperative and the methodology to work it out is the input-output (I-O) method. The suggested I-O framework may begin with sectoral transactions of the three-sector state (discussed) describing flow of commodities (water, population, and agriculture) between sectors in some abstract terms.

We can thus express the interdependence among different sectors by

$$X = AX + F$$

where,

X is the diagonalized vector of sectorial total output
A = direct input co-efficients
Z = transaction matrix ($A = Z(\hat{x})^{-1}$)
F = final demand.

Given final demand, the selection for total agriculture and water output of the region can be given by

$$X= (1 - A)^{-1} = LF \text{ (Leontief Matrix)}$$

Given the total output X, the sectoral land(use) coefficient "c" can be obtained by dividing the sectoral land (use) input (elements in M) by total output in this case (elements in X) as

$$c = M\,(\hat{x})^{-1} \quad (1)$$

In the next step, direct and indirect land requirements are given by R as in equation (2). The domestic sectoral total land requirement (S) is obtained by multiplying the diagonal of R as in equation (3). Dividing these numbers by population should give the regional ecological footprint (EF) for the sectors discussed.

$$R = CL \quad (2)$$

$$S = \hat{R}\,F \quad (3)$$

It is pertinent to mention here that the above is a suggestion in a structurally skeletal form which needs to be developed into a full fledged methodology. However, if feasible, the elements of the regional economy, considering it as an open system can be looked into and the net sectoral EF may be calculated.

CONCLUSION

During this study, all the components of the natural system of the area have been holistically examined and their interrelationships discerned, with an emphasis on The linkages of each system in the hierarchy.

There was a sudden spurt in the population growth rate to about 35%-40% in The decades beginning around 1950 in the Baruipur block. In the 70s and 80s the official figure indicates a lower growth of population, which again peaked to nearly 30% in the 90s. The water extraction from the shallow aquifers was put under great pressure to feed the population and provide for their economic sustenance (agriculture being the mainstay) and was driven up. Such a continuous pressure on the extraction of groundwater for more than a couple of decades (and even today in almost all the eastern districts) was enough to trigger reductive microbes to activate. And the natural shallow groundwater ecosystem first collapsed, followed by the agricultural ecosystem (high levels of arsenic contamination in the food chain) and health system (human ecosystem). Such a consistent pressure led finally to the collapse of the whole natural/environmental system. The denizens of the Bengal basin including those from the present area of study began to show symptoms of arsenic poisoning in the 80s. Medical research suggests that 6 months to 15 years of arsenic exposure, depending on the arsenic dose, may affect the total population, all the more so when arsenic is conspicuous by its presence in drinking water and in the food chain (Govt. of West Bengal reports).

The external human intervention on the natural eco/environmental system during the last five/six decades through high population growth, generally exponential, over-extraction of groundwater and initiation of microorganisms has nucleated the abnormal increase of arsenic content in the groundwater, reaching homeostasis at a level of 0.05-3.00 ppm. If over-extraction of aquifers continues in the coming decades at an increasing rate with an unfettered human population growth, it may be expected that the decade ending up in 2020 will see the next systems collapse, with arsenic content normalized at a higher level in the shallow aquifers.

Looking back, discontinuities and possible occurrences of collapse are discernible in the ecological systems. It is more so when one or a group of inherent subsystems is/are under pressure and overshot (Living Planet Report - WWF - India, 2006). Such systems being in the vicinity of chaos should necessarily have initial states in the neighborhood vulnerable to perturbations. The latter scenario is all the more buttressed by observations as cited above. Hence the treatment requires seeking changes in qualitative terms rather than purely quantitative data.

System collapse does not at all belong to a common vocabulary in science and technology. A real-life instance of systems collapse and chaos was observed in the Soviet economy and the nation disintegrated. Analysis shows that this was due to an accumulated effect of long-term errors in the allocation of resources. Similarly in the present basin, due to high rate of population increase, the allocation of services from different systems (because of the shifting of demand of one ecosystem to the other far an apparent solution, e.g., to provide drinking water and feed the enormous population, water is to be over-extracted, agriculture has to be stepped up which cannot be sustained by the natural water-ecosystem balance) has overshot the ecological capacity/ecological footprint leading to ecological deficit and systems collapse. A continuous error in the natural resource allocation system in the Bengal basin on account of a fundamental conceptual flaw is finally ending up in the environmental systems collapse.

A resemblance can be drawn from the occurrence of a large scale fault which may give rise to an earthquake. We consider a fault as an array of asperities with a statistical distribution of strengths. When an asperity fails, the stress on the failed asperity is transferred to one or more adjacent asperities. Existence of a critical applied stress is indicated at which the solution is bifurcation. At stresses less than the critical stress, no asperities virtually fail on a large scale. Above the critical stress, asperity failure descends/drops off from the nucleus of failure as our present case may eventually prove to be.

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