RADIOACTIVITY IN THE HYDROLOGIC ENVIRONMENT

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ABSTRACT

Certain proposed uses of nuclear explosives for peaceful purposes will introduce radioactive debris into the natural hydrologic environment. Consideration must therefore be given in each situation to the extent and significance to man of resulting radioactively contaminated water. For contained underground detonations, space-time-concentration predictions of radioactive materials in ground water are dependent on several factors: radionuclide production and initial distribution, radioactive decay, sorption on geologic materials, and dispersion during hydrologic transport. For uncontained (cratering) detonations, other aspects of the hydrologic cycle, particularly rainfall, and watershed characteristics must be considered.

Programs sponsored principally by the U. S. Atomic Energy Commission have investigated these factors. Examination of their net effects on radioactivity concentration in water shows that areas, if any, underlain by water exceeding permissible concentrations tend first to increase in size, then decrease, and finally disappear. Hydrologic processes at the surface remove or redistribute radioactive debris deposited on a watershed to other locations.

Where sufficient information is available, predictions of location and concentration of radionuclides in natural waters can be made. Any potentially hazardous conditions arising from a particular detonation can then be evaluated.

INTRODUCTION

Drinking water and food derived from contaminated hydrologic systems are potentially detrimental to man's health

and welfare. Concern for possible human consumption of water contaminated with radioactivity dictates consideration of possible contamination of the hydrologic environment.

Radioactivity has always been present in water used by man. In fact, at times it has even been represented as beneficial. The prospect that harm is done by current consumption or use of naturally radioactive water appears doubtful in most instances. However there is no doubt that potential harm might result from uncontrolled releases of radiocontaminants from nuclear explosives, nuclear power generation, and industrial uses of radioactive materials.

The prospect for development of a major nuclear industry based on widespread use of nuclear explosives is at hand. Thus, it is quite appropriate to examine the Public Health Aspects of Peaceful Uses of Nuclear Explosives. Hydrologic contamination is relevant to this examination.

As we have heard, many types of nuclear explosive applications are under development. The presence of water in certain of these applications would be inconsistent with the objectives of the project. For example, construction of effective gas and petroleum underground storage capacity would be infeasible in active water-producing media. On the other hand, applications such as canal construction, or water resource development, inevitably would lead to contact of radioactive materials with natural waters. I should like to suggest that the significance of water contamination is not whether it may occur. Rather, the significance relates to: 1) extent of the water resource which is affected; and 2) steps which can or must be taken to preclude use of unacceptably contaminated water.

Prediction of extent of contamination of the hydrologic system by radioactive contaminants produced by an underground nuclear detonation requires analysis of the undisturbed hydrologic system. Prediction also requires knowledge of the relationship of the explosion zone to the hydrologic regime and characterization of radioactive contaminants in the explosion zone water.

Processes of sorption, dispersion, and radioactive decay which take place both in the explosion zone and in the hydrosphere outside the explosion zone must be considered. Because of unique combinations of nuclear devices, explosion application, and hydrologic system, each event-related evaluation of hydrologic safety tends to be unique.

Fortunately, the basic understanding of radioactivity in the hydrologic environment is relatively well advanced

in large part through programs sponsored by the Atomic Energy Commission and its laboratories. Important contributions have been made by the Lawrence Radiation Laboratory, U. S. Geological Survey and others. Public safety and public assurance programs conducted in conjunction with the weapons testing program have been supported by the Nevada Operations Office (NVOO). Much that is applicable to peaceful uses of nuclear explosives has been learned in these studies. Non-testing nuclear programs have also made advances in hydrologic safety.

For the purposes of this paper however, I shall rely primarily on material developed under the hydrologic safety program of NVOO under Contract AT(29-2)-1229. I shall quote occasionally from NVO-40,[1] Technical Discussions of Off-site Safety Programs for Underground Detonations, and BMI 171-016, [2] Hydrologic Redistribution of Radionuclides around Nuclear Excavated Sea-Level Canals in Panama and Colombia. This study was supported in part under subcontract with Battelle Memorial Institute Management Contract for Radiological Safety Feasibility Inter-oceanic Canal Studies under AEC Contract AT(26-1)-171. For more detailed information reference to these reports is recommended.

I should like in this discussion to cover briefly the following points as they relate to predictions of hydrologic contamination:

1) The hydrologic environment and its relationship to explosion effects.

2) Interaction between radionuclides and water.

3) Hydrologic transport and prediction of space- time-concentration of radioactive contaminants.

4) Confidence levels in estimation of water contamination.

5) Surveillance of Water Quality.

6) Contamination Control.

7) Implications of water contamination.

THE HYDROLOGIC ENVIRONMENT

It may be well first to review briefly the nature of the hydrologic environment and specifically the hydrologic cycle. Figure 1 shows the essential elements of the hydrologic cycle. Precipitation as rain or snow ultimately either

runs off into streams or lakes or infiltrates into the soil. Percolation to the water table (zone of saturation) results. Ground water flows in a direction dictated by hydraulic potential, i.e. from regions of higher hydrostatic to lower hydrostatic potential. Springs, lakes, rivers, plants and the ocean are replenished with fresh water. Water leaves the ocean, lakes and rivers by evaporation, and plants by transpiration.

A diagrammatic model containing essentially these same features is shown in Figure 2. Elements of precipitation, runoff, infiltration, recharge, groundwater flow, etc. are identified. An analogous diagrammatic model of radionuclide redistribution by water can be drawn as shown in Figure 3. This model indicates movement and storage of radionuclides.

Volatile constituents, for example tritiated water, will travel all paths of the hydrologic cycle. Soluble radionuclides move with the water except during evaporation but are retarded because of plant uptake and sorption on soil and rock particles. On the other hand, movement of particulate matter is largely restricted to surface water because of the filtering action of soil and rock.

Subsurface conditions assume particular importance because intimate contact between water and essentially all of the radioactive debris is possible.

The relationship of detonation effects to potentiometric surfaces is shown in Figure 4. Four detonation conditions are depicted schematically at varying scaled depths of burial corresponding to conditions of crater formation to complete containment.

If the potentiometric surface, or water table, is below all explosion effects the hydrologic contamination possibilities are minimal. They would be limited to recharge from surface water, downward infiltration and radionuclide transport through unsaturated medium. Contamination of ground water ultimately might result.

If the potentiometric surface is shallower but still beneath surface features, infill of rubble chimneys and crater fallback occurs. Where potentiometric surfaces are just below ground surface infill occurs. When an excavation or subsidence crater bottom is below the potentiometric surface a radioactive lake may form during readjustment of the potentiometric surface. If loss by evaporation is sufficiently low in relation to subsequent precipitation contaminated water will also flow into the ground water system from the crater in response to elevation of the hydrostatic level within the

crater. Outflow could result if a crater or rubble chimney intersects confined aquifers which have hydraulic potentials above ground level. This corresponds to an artesian condition.

Fallout from cratering detonations is subject to leaching by rainwater. Contaminated water may infiltrate the groundwater system, run off the surface, or be subject to plant uptake. Ultimately, by either surface or subsurface transport radionuclides may enter lakes, streams and the ocean. Decreases in concentration of dissolved radionuclides will be caused by dilution, dispersion, decay and sorption. Reconcentration within the biosphere is a possibility.

Whenever a nuclear device is detonated below the potentiometric surface, the result is formation of a sink as shown in Figure 5. Ground water flow will be initially toward the sink until the potentiometric surface reaches equilibrium as shown in Figure 6. At this time outflow from the rubble in the explosion zone begins.

During outflow from the explosion zone, contaminated water adjacent to the downstream side of the explosion zone will immediately enter the hydrologic system. Contaminated water within the explosion zone will be subject to processes that will change the concentration of the contaminant with time, such as dissolution of radionuclides from explosion debris and sorption or desorption of radionuclides upon surfaces produced by the explosion. Uncontaminated water entering the upstream side of the explosion zone also will become contaminated as a result of desorption and dissolution of radionuclides from rock surfaces as it moves through the explosion zone.

Only simple examples of contamination of the hydrosphere by underground nuclear detonations have been discussed. It is probable that the section of rock intersected by the rubble chimney will consist of zones with varying hydraulic potentials and transmissivities. This hydrologic system, as modified by the nuclear detonation, will be complex. Interflow between aquifers, or outflow from craters might result. An analysis of the hydrologic system and of changes in the system caused by nuclear detonations is of utmost importance for predictions of hydrologic contamination.

WATER CONTAMINATION SOURCE TERM

Consideration will be given next to movement of the contaminated mass of water through the undisturbed hydrosphere. Transport equations have been developed which enable calculation of time- space- concentrations of radionuclides. Primary input for these equations is the water contamination

source term. This source term is the initial concentration of radioactive contaminants in the explosion zone water where it is flowing out of the explosion zone. To provide the source term one requires the quantities of radionuclides produced initially and their spatial distribution in the explosion zone water.

The species and quantities of radionuclides are determined by device design and composition of the surrounding geologic emplacement medium and stemming materials. They can be estimated from knowledge of device design and performance.

Radioactive contaminants probably will not be distributed uniformly throughout the explosion zone. Actual concentration distributions have been measured in the field but too few data have been obtained as yet to produce a satisfactory theory. Present hydrologic contamination predictions assume conservatively that the radioactivity is evenly distributed through the explosion zone water, and that it is in water soluble form.

To complete the source term calculation it also is necessary to evaluate the effect of transporting the contaminated water out of the explosion zone.

Without going into a detailed discussion, it will be appreciated that such effects will be related to the character of the detonation and the hydrologic regime pertaining to each detonation.

For purposes of illustration let us consider contained detonations and return briefly later to consideration of some aspects of cratering detonations.

For the condition where flow is from the explosion zone into the ground water system the source term input to the transport equations will have a sharp front and a dispersed tail as shown in Figure 7. Dispersion, which relates to the distribution of velocities about the mean water velocity, in the explosion zone is responsible for this effect. The radionuclide transport equation requires a rectangular source term. The more complex but probably more realistic source term is approximated with a series of step functions.

The concentration of radionuclides in water in contact with rubble of course cannot be derived solely from solubility or consideration of solubility product constants of compounds in which they occur. Sorption of dissolved radionuclides on rock surfaces or sediments reduces concentrations to values below those derived from such determinations and retards the movement of the radionuclides relative to the water velocity.

Water in the explosion zone and in the aquifer is in contact with large surface areas on which sorption can occur.

The sorptive potential for various radionuclides on solid surfaces is determined by measuring the distribution coefficient (K_d) for the radionuclide. Rock and water from the zone of interest are used, if possible, in laboratory measurements of K_d. The distribution coefficient is defined as:

$$K_d = \frac{\text{Activity of the radionuclide in the solid}}{\text{Activity of the radionuclide in the water}} \times \frac{\text{Volume of water}}{\text{Mass of solid}}$$

For the range of rock-water combinations, distribution coefficients for radionuclides have been found to vary over two to three orders of magnitude. The distribution coefficient for a radionuclide is a quantitative index of the partitioning of the available quantity of that radionuclide between the solid and liquid phases of the system.

For example, a measured distribution coefficient of 100 would indicate that about 1/600 of the available element is in the water and the rest is sorbed on the rock surfaces. In a rock the ratio of volume of water to mass of solid is a function of the porosity.

TRANSPORT OF RADIOACTIVE CONTAMINANTS

Having defined the idealized source term-- the initial body of contaminated water-- we can examine its subsequent movement through the hydrologic system. This movement takes place of course in the down gradient direction. The rate of flow of water outside the rubble and fracture zone is that of the natural system. But, the rate of transport of radionuclides is less than the rate of flow of water. Sorption causes radionuclides, excepting possibly tritium, to be retarded relative to water.

The retardation of sorbed radionuclides is expressed by the following equation:

$$\text{Flow rate of Radionuclide} = \frac{\text{Flow Rate of Water}}{\text{Retardation Factor}}$$

The retardation factor B is

$$B = 1 + \frac{1 - \theta}{\theta} \rho \ K_d$$

where

θ = fractional porosity

ρ = grain density of rock

K_d = radionuclide distribution coefficient

K_d was defined earlier as $\frac{As}{A_w} \times \frac{Vw}{M_s}$

Since the retardation factor is dependent upon both porosity and K_d, the retardation factor theoretically can vary from one to infinity. In practice retardation may be great enough essentially to stop movement of the radionuclide. An interesting point is that if, for example, 99% of the radionuclide is sorbed it will travel at 1% of the average water velocity. That is, the bulk will travel at this rate. Some of the radionuclide will travel as fast as the water (theoretically). K_d and B merely make it possible to relate measurements on the same material in different physical states.

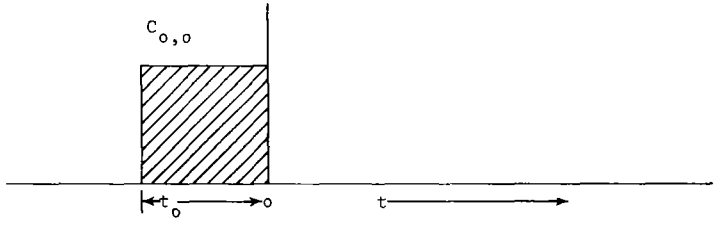
The redistribution of a radioactive contaminant can be described by a hydrodynamic transport equation as discussed by Fenske.(1) This equation, currently being used in the NVOO safety program, is an analytical solution in one dimension of the differential equation describing transport of contaminants through porous media. The two-dimensional distribution in a horizontal plane can be approximated by including an equation to estimate the effect of lateral dispersion.

Dispersion was defined earlier as the variation of water velocities about the mean velocity. Variations in mean velocities of water between streamlines through the aquifer as well as the explosion zone result in mixing of contaminated water with uncontaminated water, causing dissipation of sharp interfaces between contaminated and uncontaminated water during hydrodynamic transport. During the transport of contaminated water out of the explosion zone, the leading edge of the contaminant immediately enters the hydrologic system where, of course, it is subject to dispersion in the transport equation. The trailing edge of the contaminant slug, however, is also subject to dispersion resulting from transport within the explosion zone.

Because of the inherent stratification of most rocks, the large horizontal distances compared to vertical distances involved, and the desirability of considering outflow at different outflow points along the vertical dimension of the explosion zone, the vertical dimension is not considered in the transport program, but can readily be modeled by using

the superposition of rectangular source terms as described earlier and shown in Figure 7. A large number of calculations are required to describe temporal-spatial variations of concentrations of the radioactive contaminant. To facilitate making the calculations, the transport equation has been programmed for a computer. The form of the transport equation defined by Fenske and Holly[3] is:

$$C(x,t)=\tfrac{1}{2}C_{o,o}\ \exp(-\lambda t)\left[\operatorname{erfc}\frac{x-vt/B}{2\sqrt{Dt/B}}-\operatorname{erfc}\frac{x-v(t-t_o)/B}{2\sqrt{D\,(t-t_o)/B}}\right]$$



Contaminant Transport Equation

Where

- t = time measured from when the explosion zone outflows
- t_o = the original length of the slug in terms of time of transit
- x = distance from explosion point measured along a streamline
- λ = radioactive decay constant of the radionuclide
- v = the average seepage velocity of ground water
- $B = 1 + \frac{1-\theta}{\theta}\rho K_d$ = retardation factor
- θ = porosity of the aquifer
- K_d = distribution coefficient of the radionuclide between the solid and aqueous phase of the hydrologic system
- D = dispersion coefficient
- $C_{o,o}$ = initial concentration of radioactive contaminants
- $\frac{Dt}{B}$ = one-half the variance of the radioactivity concentration curve

The equation describes the transport of a slug of contaminated water that was originally rectangular. The first term in the brackets represents the effect of transport on the front of the slug. The second term in the brackets represents the effect of transport on the rear of the slug. The exponential modifier preceding the bracketed expression corrects for radioactive decay.

The solution presented above is not a complete solution. Several terms have been neglected because the simplication obtained is great and the error caused by the neglect of these terms is small.

In most underground nuclear detonations the porosity and permeability of the explosion zone will be higher than the porosity and permeability of the surrounding undisturbed rock. As the contaminated volume of water flows into the ground water system it will occupy a larger volume of rock because of the smaller pore volume available and be lengthened in the longitudinal direction because of the higher ground water seepage velocity. The area underlain by contaminated water in the ground water system will be larger and of a different shape than the area underlain by contaminated water in the explosion zone. This effect is illustrated in Figure 8.

Output from the program is a series of matrices that can be converted into contour maps predicting the area distribution of radionuclide of interest with concentration isopleths. The present state-of-the-art does not permit the calculation of absolute concentrations with a high level of confidence. Ultimately a higher level of precision in concentration calculation should be possible. The probability is high, however, that calculated concentrations are equal to or above the actual concentrations. At the present time, instead of contouring concentrations, a line is drawn bounding the area which includes, with a high level of confidence, all concentrations above the maximum permissible concentration (MPC) for drinking water. Such a delineation is shown in Figure 8. Note expansion and contraction of areas underlain by concentration in water exceeding MPC. Similar contouring of concentrations up to 5xMPC have also been carried out.

Whether MPC or concentrations in water above or below this level are relevant is outside the exclusive purview of the nuclear hydrologist.

The objective of the nuclear hydrologist is to provide those physical data on water contamination from which an evaluation of potential hazard can be made. By AEC directive values in current use in the NVOO safety program are based

upon concentrations given in USAEC Manual, Chapter 0524, Standards for Radiation Protection, Annex 1, Table II, Column 2, and reduced by a factor of three to be consistent with guidelines for uncontrolled areas.

Reference has been made to hydrologic effects in nuclear craters. Craters may serve as a direct route for transfer of radionuclides into ground water. The reverse condition may also obtain where ground water infiltrates into the crater carrying soluble radionuclides with it. For the condition of a cratering detonation it also is necessary that transport of dissolved or suspended fallout and crater ejecta be considered. This situation is more complex than that discussed earlier but is amenable to modeling and calculation. Consider the transport of contaminants dissolved by rainwater as developed by Charnell, Zorich and Holly.[2] As rainwater impinges on the soil surface, it contacts fallout radionuclides, some portion of which go into solution. Dissolved radionuclides are transported by runoff or soil infiltration. Infiltrating water does not enter ground water directly but is subject both to evaporation and to transpiration near the surface in the root layer. In some tropical areas of high rainfall, runoff normally occurs in a layer near the surface rather than over the surface. Percolation to ground water occurs under favorable conditions. The proportion of a radionuclide that travels either to a stream or to the ground water depends upon the rate at which the rainwater percolates below the surface layer. In general, rate of infiltration varies with time in a manner dependent upon precipitation history for the watershed. Following a dry period, infiltration rate is relatively high. The rate will decrease during a storm, due to alleviation of soil moisture deficiency, swelling of colloids, and compaction of the surface by raindrops. The total amount of dissolved radionuclide removed in runoff is determined by the ratio of runoff water to total water available.

The ground water system acts as a reservoir for water and dissolved radionuclides which are eventually discharged into streams. Migration of a radionuclide through the soil will be retarded relative to water due to sorption as discussed earlier.

As this brief description suggests, the complexities of the total hydrologic radionuclide transport system are very substantial.

Simplifying assumptions were necessary not only to reduce the problem to manageable size, but for correspondence between the degree of sophistication of the transport models and accuracy or availability of field data.

A summary of the equations which express quantities of radionuclide removed from the watershed in terms of the various hydrologic and physical variables and constants is shown in Figure 9.

Where

R = rainfall rate during the time interval Δt

I = infiltrated water

Q = runoff

ET = evapotranspiration

Q_{GW} = ground water flow

ΔNL = amount of radionuclide removed per unit area by leaching alone

F_w = fraction of radionuclide in the water $\left(\frac{1}{1 + \frac{1}{\alpha} K_d}\right)$

R_u = unit rain

N = amount of radionuclide on the soil surface

N_R = total quantity of radionuclide in the runoff for the time interval Δt

A = area of a watershed

N_I = amount of radionuclide in infiltration

N_G = amount of radionuclide in ground water

B_F = volume of base flow over the time interval

N_A = total radionuclide present in the reservoir

α = ground water reservoir porosity

H_r = effective thickness of the reservoir

This general model was applied by Charnell, et. al., to Route 17 in Eastern Panama. For this application it was necessary to divide watersheds into homogeneous subunits. Figure 10 shows for the fallout zone the sub-watersheds which were selected. Subdivision was accomplished by considering: 1) precipitation amount; 2) precipitation runoff interrelation; and 3) initial radionuclide deposition. Size of the areas near the canal alignment were kept somewhat smaller than those farther removed in view of the greater variation and concentration of fallout deposition in this region.

As an example, at a use point just down river from El Real, water is contributed from both the Chucanaque and Tuira Rivers. At that point, water and radionuclide would

be contributed from sub-watersheds denoted as 6, 7, 8, 9, 11, 12, 13, 14 on Figure 10. Field information indicated that these sub-watersheds have similar geologic and hydrologic characteristics.

It was assumed that strontium in fallout might be distributed in an exponential manner away from the canal at completion of excavation. This was represented by one activity unit per square kilometer (A.U. km^{-2}) on sub-watersheds 6, 7, and 11, decreasing to 0.0001 A.U. km^{-2} on 14.

Following deposition, rainwater would leach strontium from the fallout and carry it downstream to the use point. A precipitation pattern was approximated by using the average quarterly rainfall rates. Some of the results of the calculations are the following:

> After one year, about 20% of the initially deposited strontium was calculated to have been removed from each sub-watershed surface by leaching and radioactive decay. Surface runoff would carry this material past the use point with a concentration, at the beginning of the year, of about 10^{-10} A.U. per liter. Near the end of the year the concentration of strontium-90 in the river water would decrease only by a factor of 2 to 0.5 x 10^{-10} A.U. per liter. During this same period, ground water would contribute strontium to the use point in a concentration that is nearly 4 orders of magnitude lower than that by surface runoff.
>
> A smaller distribution coefficient would cause a much higher concentration in the river water initially. Removal by leaching would be very effective and the concentration in river water would decrease rapidly. By extrapolation tritium with a very low distribution coefficient, would be removed from the surface almost entirely by the first rain. There would be a tritium surge in the river associated with this runoff but subsequent surface water runoff would contribute a negligible amount of tritium to the stream. After the first rain, the only device associated tritium in the river would come from the ground water. The annual contribution of tritium by ground water outflow from a watershed was calculated to equal about 10^{-3} of the total tritium deposited on the surface as fallout.

CONFIDENCE LEVELS

A necessary part of any estimate of contamination by nuclear explosion-produced radionuclides is an indication of the confidence that can be placed in the analysis. Field checking of hydrologic safety program predictions is costly and necessarily requires considerable time. The present hydrologic safety program therefore, lacks the field data necessary for confirmation of contamination estimates. For this reason, all expressions of confidence levels must be matters of scientific judgment. Although they are subjective, they possess useful validity.

The output from the NVOO-sponsored hydrologic safety program as discussed by Fenske,[1] is the temporal-spatial variation of concentration of the radioactive contaminant. Numbers specifying time, position, and concentration can have attached to them their standard deviation. This can be done by estimating the uncertainty of each factor contributing to the analysis and combining these variances in an error propagation equation to calculate the expected variance in the analysis. This confidence level, in other words, specifies the most probable value and the variation about this value that might be expected. Considering the state-of-the-art, these confidence levels are low. This technique not only determines the error in the analysis but also determines which component makes the largest contribution to the error and indicates where maximum improvement can be effected.

Alternatively, a statement of confidence can be made that the real concentration is equal to or less than the predicted concentration. Using the philosophy of selection of the credible but conservative input for all variables, upper limits on concentrations of radionuclides can be made with a high level of confidence.

Likewise, therefore, maximum exclusion areas can be stated with a high level of confidence. Much lower confidence levels must be associated with estimates of actual volume of the water resource degraded by a nuclear detonation. It may reasonably be expected that future studies will demonstrate that smaller volumes of water than presently stated are unacceptably contaminated, and that smaller sites or exclusion areas than presently used are acceptable for nuclear detonations.

It is very interesting to note that large (order of magnitude) errors in estimates of the absolute concentration of a radionuclide in the explosion zone water can be

tolerated. Fenske illustrates this point with the following example for tritium:

> Assume the probable concentration of tritium in the explosion zone water is 1800 times MPC and the range of possible concentrations is from 400 times MPC to 3200 times MPC. The actual concentration not atypically might be expected to fall within this range 99.7% of the time. This water enters the hydrologic system. Although the upper limit of the range of possible concentrations is nearly an order of magnitude above the lower limit, the difference between the limits is equivalent to a decay time of only three half-lives. At ground water velocities of 60 meters per year, the contaminated volume will be transported about two kilometers farther before decay below MPC if the concentration is at the upper limit of the range than it is if at the lower limit. In such a case the range in location due to the possible range of concentration would be about 2 kilometers. At the one sigma level the error in location would be 370 meters. After several tens of years of transport this is a smaller error than that in an estimate of ground water velocity and direction.

SURVEILLANCE

The prediction of water contamination provides a basis on which to plan post-shot water utilization. However, once radioactive contamination has been introduced to the hydrologic system, surveillance is necessary to provide evidence of arrival or non-arrival of contaminants at a use point. Normally, appearance of water contaminated well below MPC would be of extreme interest in order that a monitoring program could be started and remedial measures initiated. The measured background radioactivity of natural waters varies considerably. This scatter of data can be attributed to errors in sampling, errors in analysis, and natural fluctuations within the hydrologic system. Assessment of the significance of data scatter by statistical methods is required where fluctuations in radioactivity of the sample are close to those of the natural system.

Dr. John Sharp,[4] Desert Research Institute, University of Nevada, has developed such statistical methods. Serial correlation, quality control and non-parametric techniques have been developed. These techniques are intended for recognition of uptrends associated with breakthroughs of

explosion radioactivity which are superimposed on the pre-existing natural radioactivity of the water. Interpretation of analytical results has been aided by computerized statistical analysis techniques and development of a storage/retrieval system for monitoring data.

An adequate surveillance program involves collecting and analyzing enough pre-detonation samples to establish the natural background radioactivity of the water so that valid comparisons with post detonation water samples are possible. Satisfactory determinations of background radioactivity require the analysis of sequentially collected samples from each sampling point.

A post-detonation, sequential sampling program is needed to provide assurance on a long-term basis that contamination has not appeared at use points. If it has appeared at use points or monitoring points it may indicate the need for remedial measures or hydrologic controls.

HYDROLOGIC CONTROL OF WATER CONTAMINATION

Remedial or control measures may be instigated upon detection of breakthrough. They also may be applied at an earlier stage as part of a planned program of water utilization in the region of nuclear detonations.

As stated earlier, the rate and direction of flow of contaminated ground water is influenced by the character of the potentiometric surface. If this is known with sufficient accuracy it becomes possible to predict space-time-concentrations of contaminants, and plan water withdrawal so as to avoid the contaminated water body.

Techniques for hydrologic control have been employed for many years to control saltwater intrusion, flow of natural hydrocarbons, etc. Such techniques also are applicable to control of the movement of the body of contaminated water. One can for example, visualize pumping into injection wells outside the rubble chimney in such a way as to raise the potentiometric surface around the rubble chimney and temporarily immobilize the body of contaminated water. Similarly, it should be possible to divert, accelerate, or slow movement of contaminated water in order to optimize withdrawal and use of uncontaminated water. The use of aquifer grouting to reduce permeability selectively has been suggested but not evaluated. Whether these techniques can find application is largely an economic question. Certainly the most economic case is where contamination control can be exercised through accurate hydrologic analysis, a well designed

monitoring program, and a corresponding water use plan which avoids the region through which contaminated water is passing. Typically, such passage might be complete within a few years. Dilution with uncontaminated water or water treatment could be considered. Other ameliorating approaches, where water contamination becomes a limiting factor may include optimization of yield, and device emplacement. By this means it may be possible to avoid water bearing zones, or involvement of hydrologic regimes which unnecessarily bring contaminated water to use points. In the case of cratering detonations techniques might be developed for minimizing release of radioactive debris to the surface environment. Since tritium appears to represent the greatest potential for off-site water contamination, selection of low fusion, high fission devices would be preferable in a hydrologic environment if other considerations are not controlling.

For some projects, a well designed monitoring system may provide all the protection required for public safety if planned in conjunction with remedial measures should these be found desirable.

IMPLICATIONS OF HYDROLOGIC CONTAMINATION

I would like to comment at this point on some additional implications of hydrologic contamination.

It has been noted that proposed commercial applications of nuclear explosives provide a broad range of possibilities for water contamination.

Techniques for prediction of space-time-concentrations have been developed and applied. Given applicable standards, acceptable sources of water can be delineated from unacceptable sources, and the extent of a natural resource, water, that must be withdrawn from human and animal use can be determined. Optimum water utilization programs can be designed or remedial hydrologic engineering projects undertaken. The analogy can be drawn with established practices for limiting releases of radioactive wastes into the environment from nuclear power plants, production plants, and other industrial activities. It should be possible to design nuclear explosive applications which would result in at least comparable safety features.

It is important to note a basic difference between prospective hazard from hydrologic contamination and some other hazards, at least insofar as use of water for domestic purposes is concerned. This difference is related to the time delay between detonation and potential exposure.

In general, the time between detonation and exposure to water contamination is much greater than obtains for seismic effects or airborne contamination. There is adequate time for analysis of water to determine whether unacceptable contamination exists. Also, there is time to instigate remedial measures or develop alternative water supplies. There is not the urgent need to drink contaminated water that there is to breathe possibly contaminated air. Inadvertent use of contaminated water can be prevented. It is difficult to conceive of applications where this is not so. Thus, the concern for water contamination can be translated into a consideration of economics rather than hazard. The question is what does it cost to buy safety? It can be bought at some price perhaps as a *maximum*, at the cost of an alternate, water supply for a number of years. Consideration has been given to risk-benefit aspects of applications of nuclear explosives. However, hydrologic safety is really a matter of cost-benefit. Cost-benefit calculations, of course, will be associated with uncertainties represented by the uncertainties of predicting the hydrologic contamination.

But, for any preselected criteria, the nuclear hydrologist can be expected to estimate the probable cost of insuring a safe water supply, and to place upper and lower limits on his estimates. By this means the economic feasibility of a nuclear detonation for peaceful uses can be assessed within the context of assured hydrologic safety.

REFERENCES

1. Fenske, P. R., *Technical Discussions of Offsite Safety Programs for Underground Nuclear Detonation.* Palo Alto Laboratories, Isotopes, a Teledyne Company, Palo Alto, California, U. S. AEC Report NVO-40.

2. Charnell, R. L., T. M. Zorich, and D. E. Holly, *Hydrologic Redistribution of Radionuclides Around Nuclear Excavated Sea-Level Canals in Panama and Colombia,* Palo Alto Laboratories, Isotopes, a Teledyne Company, Palo Alto, California. Battelle Memorial Institute, U. S. AEC Report BMI-171-016.

3. Holly, Donald E. and Paul R. Fenske (1966), *Transport of Dissolved Chemical Contaminants in Ground Water Systems.*

4. Sharp, J.V.A., In publication.

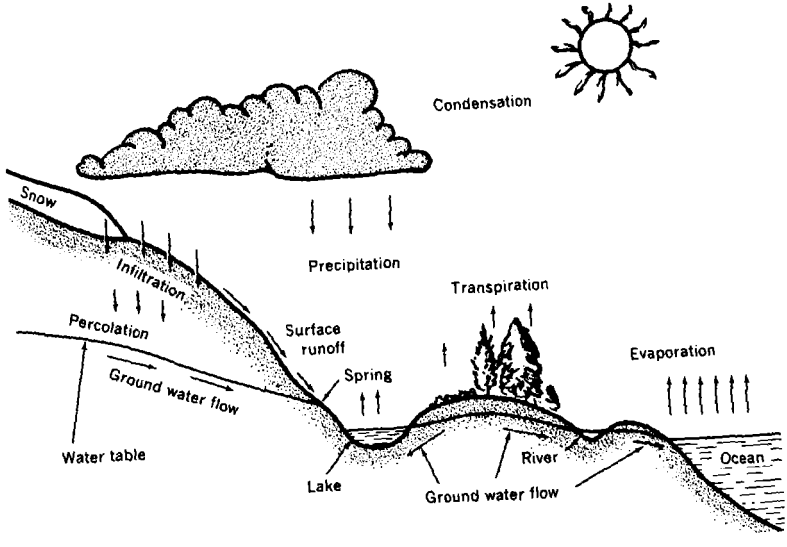


Figure 1. The hydrologic cycle.

David K. Todd. Ground Water Hydrology, Ch. 1, pg. 9

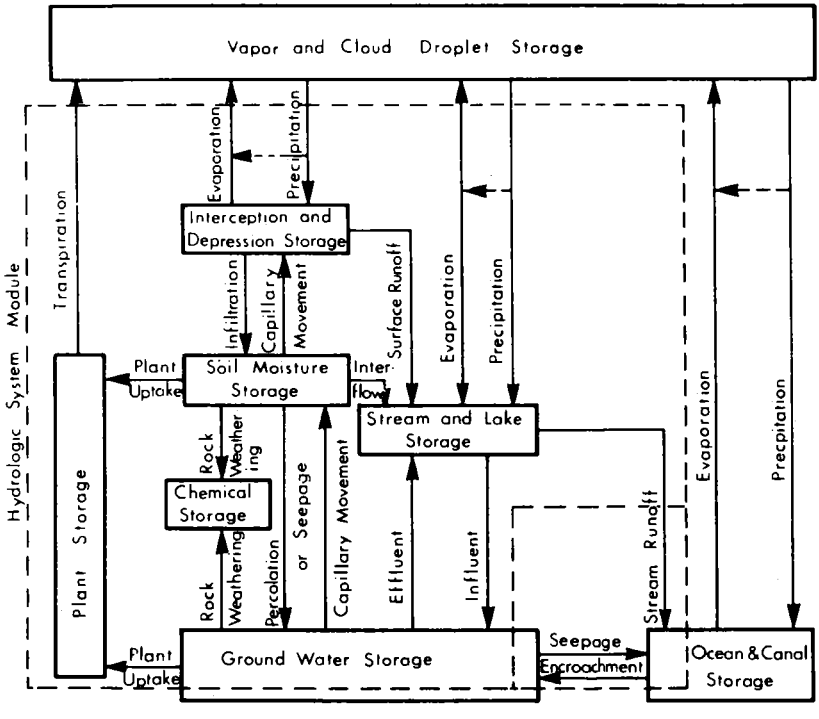


Figure 2. Diagrammatic Model of the Hydrologic Cycle.

P.R. Fenske and D. Sokol, Private Communication

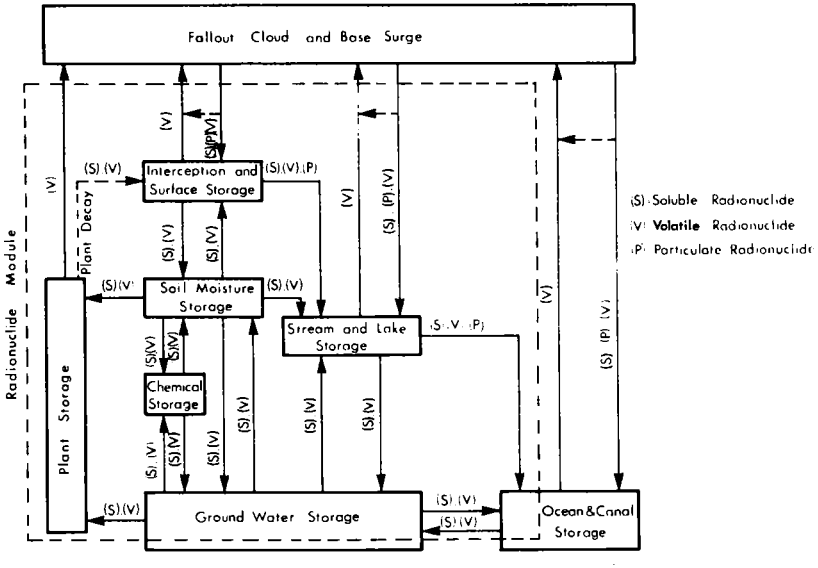


Figure 3. Diagrammatic Model of Radionuclide Transport By Water

P.R. Fenske and D. Sokol, Private Communication

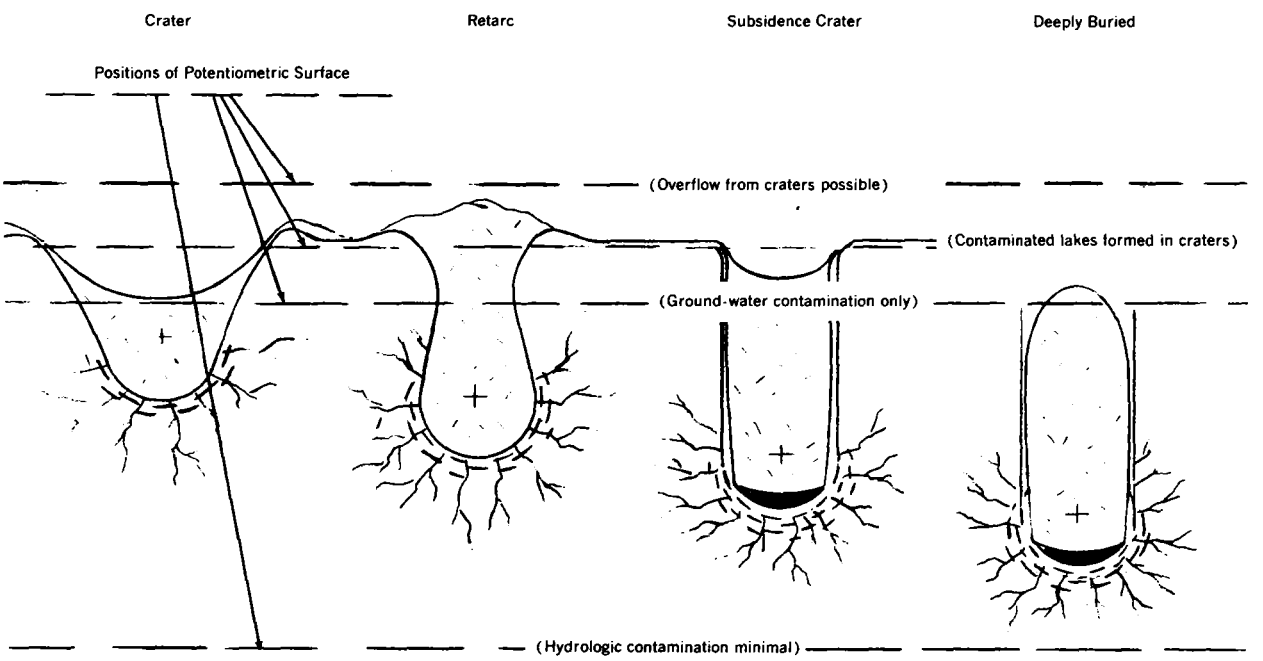


Figure 4. Relationship of Detonation Effects to Potentiometric Surface

P.R. Fenske, NVO-28(Revised) Chapter X, In Press.

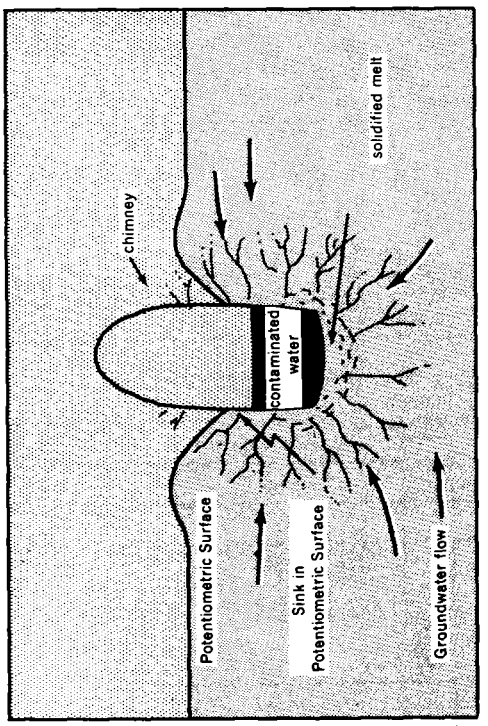


Figure 5. Readjustment of Potentiometric Surface
P.R. Fenske, NVO-40, Chapter 6

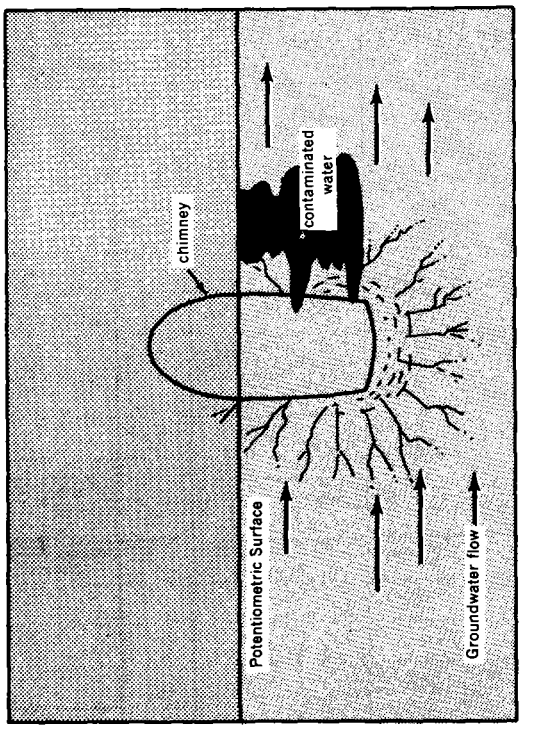


Figure 6. Outflow of Contaminated Water
P.R. Fenske, NVO-40, Chapter 6

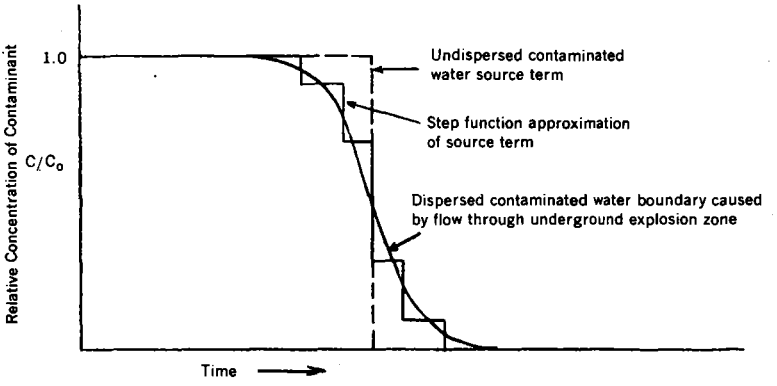
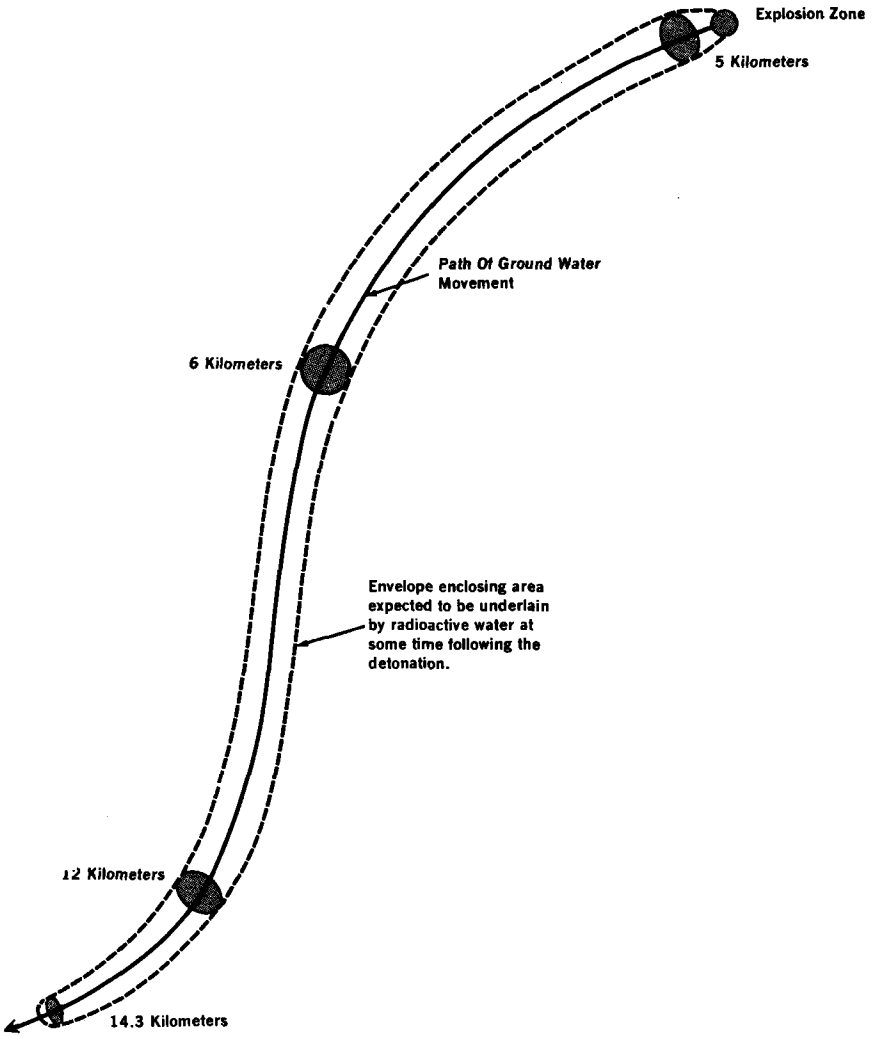


Figure 7. Source Term for Flow from Underground Explosion Zone into Ground-Water System.
P.R. Fenske, NVO-40, Chapter 6



Total Migration distance 14.5 Kilometers (approximately 145 yrs.)

Figure 8. Hypothetical Contamination Prediction.
P.R. Fenske, NVO-40, Chapter 6.

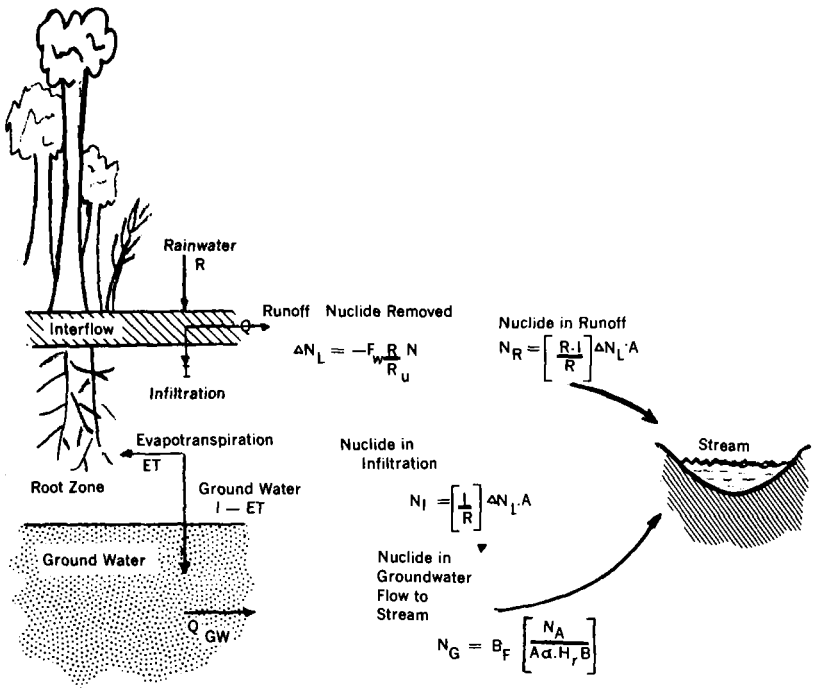


Figure 9. Schematic *Diagram of the Fallout-Zone Redistribution*
R.L. Charnell, et al., BMI - 171 -016

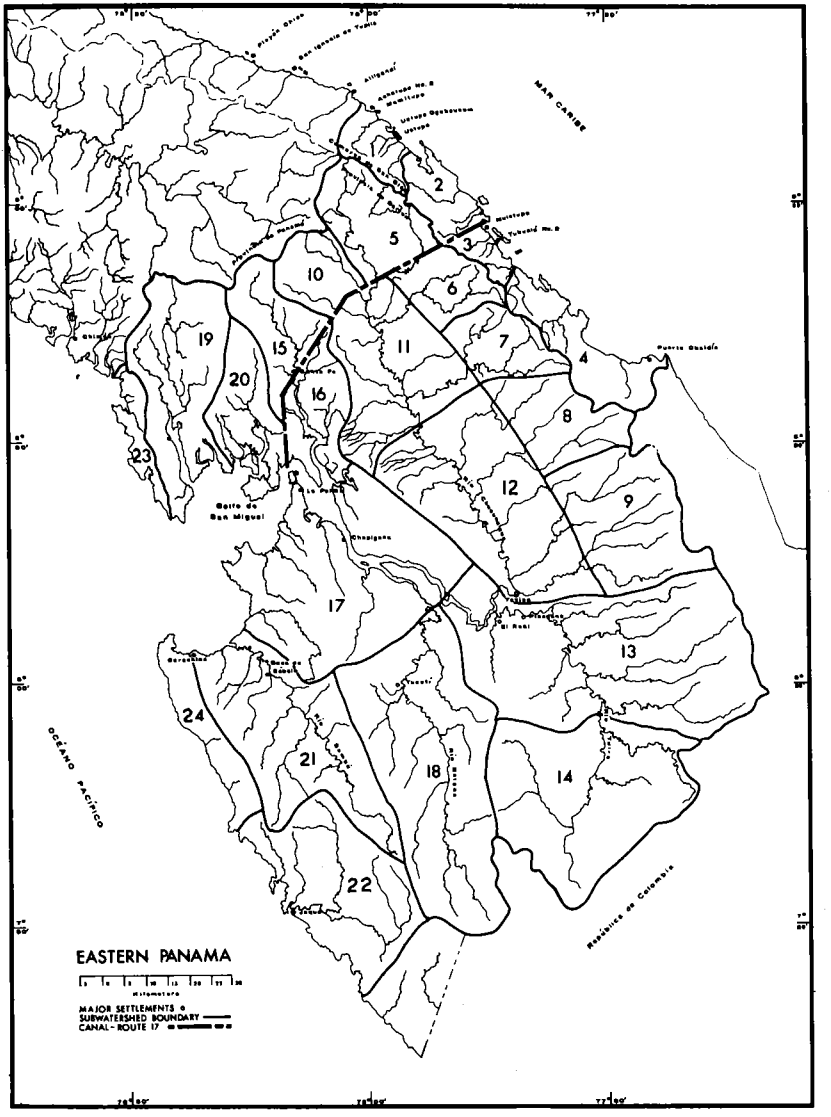


Figure 10. Delineation of Subwatersheds Around a Nuclear Excavated Sea-Level Canal in Eastern Panama.
R.L. Charnell, et al., BMI - 171 -016

QUESTIONS FOR LOUIS WERNER

1. From Dr. Lowman:

   Studies in Panama and Puerto Rico indicate that in a tropical rain forest sheet transport or sheet surface erosion is practically zero and most of the suspended river sediments are from channel erosion. What is your estimate on the reduction of the elution rate of tritium from the forest into the rivers as a result of this?

   ANSWER:

   Well, I'm not sure that there is going to be a good estimate of what this reduction will be by any means. This will be a part, I think, of the considerations coming out in the Battelle report and I am sure that this question is under consideration by the Battelle people who are responsible for it. For the study which was carried out by Charnell and others, it was necessary to make some simplifications which did not permit this factor to be evaluated, unfortunately. But, it does appear to be true that sheet erosion is not important. It appears to be true from what I hear from some of the people at Lawrence Radiation Laboratory that there is another mode of uptake of water which is directly by plants sort of a reverse of transpiration which is not an element of this model and so there will be certain adjustments that are going to have to be necessary.

2. From Alex Grendon:

   Was ρ omitted in the equation $K_f = \frac{1-\text{theta}}{\text{theta}} Kd + 1$?

   The legend defined ρ as density, but it does not appear here.

   ANSWER:

   The answer to that is yes, it was omitted. I discovered it when I was going over it in my notes and I did not call attention to it.

3. From Alex Grendon:

   Why was B used as a symbol for this same expression in a later slide?

   ANSWER:

   I think that is just the author's license. These were taken from two different investigators and one used one and one the other. I don't think there is any essential difference between them.