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FINAL TECHNICAL REPORT

EVALUATION OF FALLOUT CONTAMINATION FROM SURFACE RUNOFF

By

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and
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Covering the Period

6 November 1965 to 10 June 1966

Contract No. N228-(62479)69779

Work sponsored by
Office of Civil Defense
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OCD Work Unit No. 3131C

through

Technical Management Group
U.S. Naval Radiological Defense Laboratory
San Francisco, California

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Division of Engineering
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North Andover, Massachusetts

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ABSTRACT

Previous work in the field of water supply contamination from fallout due to nuclear attack has indicated that the level of activity brought into the water supply by surface runoff from the watershed increases the activity considerably. These studies employed a constant value for the "runoff coefficient" to obtain estimates of the degree of contamination resulting from the soluble fraction of fallout activity deposited on the watershed. The present report is part of an investigation to better define the relationship between rainfall and the amount of activity that reaches the water supply due to runoff. It concentrates mainly on two areas: the hydrology of surface runoff and ion exchange phenomena.

A detailed qualitative discussion of the relationships between the various hydrological parameters is presented. Some of the difficulties encountered in trying to predict runoff as a fixed percentage of rainfall are discussed.

Some data on ion exchange properties of soils with respect to the biologically important radionuclides are given. In addition the report includes an indication of how the information presented in the report may eventually be included in a consideration of the general problem of transport of activity, a discussion of uptake of activity by biota and some preliminary calculations of water supply contamination for Providence, R.I., one of the cities in the OCD "5-City Study".

The maximum levels of selected contaminants at the Providence water intake from a total 30 MT weapons attack were found to be approximately as follows (in μc per mℓ):

	Sr-89	Sr-90	Ru-106	I-131	Cs-137	Ba-140
Surface contamination only	5×10^{-3}	3×10^{-5}	4×10^{-4}	4×10^{-2}	2×10^{-5}	3×10^{-2}
Contamination, incl. runoff	7×10^{-2}	7×10^{-4}	1×10^{-2}	1	4×10^{-4}	6×10^{-1}

These figures indicate that the water supply contamination problem may be increased by a factor of 10 to 25 when surface runoff from the watershed is considered.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

This project, for the purpose of evaluating the contamination of water supplies from fallout due to surface runoff, was officially initiated on November 6, 1965. It is an outgrowth of previous investigations conducted to estimate water contamination and was supported then by the Office of Civil Defense under Contract No. OCD-PS-64-62 (OCD Work Unit 3131B). The results of the previous studies led to the conclusion that the degree of radioactive contamination may be significantly increased when watershed runoff, due to antecedent rainfalls, is included. Throughout the performance of this project, Dr. S. Mikhail of the U.S. Naval Radiological Defense Laboratory, Hunter's Point, San Francisco, California, has acted as Technical Officer. He has provided valuable information and suggestions which have contributed directly to the conduct of these investigations. Dr. Mikhail and other members of the USNRDL staff also aided materially with logistic support by helping to make the necessary reports and documents related to this work available as needed, providing liason with co-workers in the field and acting as a clearing house on many administrative problems.

The authors also acknowledged the support, technical assistance and advice obtained from Mr. William J. Lacy and other members of the Postattack Research Division, Office of Civil Defense, Washington, D.C. Full credit for the development of the basic fallout model used in these studies goes to Dr. Carl Miller, Senior Scientist, Stanford Research Institute, who has given unstintingly of his time and provided personal guidance and counsel. Without his valuable advice and interpretations an intelligent utilization of this model would not have been possible. Valuable information on the Providence, R.I. water supply system was graciously provided by Mr. Philip J. Holton, Jr., Chief Engineer, Board of Water Supply, City of Providence, and utilized in the preliminary calculations of water contamination.

The computer work was carried out in part at the Computation Center of the Massachusetts Institute of Technology, employing an IMB 7094 Electronic Computer.

I. INTRODUCTION

The general purpose of this study is to evaluate and summarize the problem of water contamination by radioactive fallout in the event of nuclear war. The level of fallout that might result from a possible nuclear attack was based on current theories of the formation and distribution of fallout.

The potential degree of water contamination from fallout was evaluated and estimates of the biological hazards associated with the ingestion of fallout contaminated water following hypothetical nuclear attack presented (1). The potability and biological effect of contaminated water supplies were questioned. The availability and use of water supply are most important to a community during the postattack period. From previous investigations it appears that surface runoff may contribute significantly to the contamination of water supplies, depending on environmental factors including watershed characteristics and meteorological aspects (*). Therefore, it was proposed to conduct a detailed analysis of the redistribution of fallout and the contribution to contamination from surface runoff during the early postattack period from land areas to streams and from watersheds into reservoirs. The analysis of the redistribution phenomenon is equally important in and around urban centers where the activity concentration may change significantly following precipitation, especially for the soluble nuclides. From the previous studies it appears that surface runoff from rainfall during the first 24 to 48 hours following nuclear attack will be critical as far as water contamination is concerned.

(*)Results of these studies indicated that the contribution to water contamination due to surface runoff may be significantly greater than that due to direct contamination by a factor of 10 to 25. When the effect of watershed runoff was included, contamination levels exceeding 10^{-2} $\mu c/m\ell$ for I-131 and Ba-140 were obtained.

II. OBJECTIVES

The objective of these investigations are: (1) to conduct a detailed analysis of the degree of contamination of water supply systems due to runoff, (2) to use these results to estimate the dose absorbed by human body over different periods of water consumption, and (3) to contribute to the OCD 5-city study by evaluating fallout contamination of selected water supplies.

To determine the mechanism by which fallout activity is transported by the runoff and contributed to water supply contamination it is necessary to study the variables affecting runoff; including hydrologic, meteorologic and geologic aspects, investigate the solubility, ion-exchange, biota uptake, transport and redistribution of radionuclides in water and over land and to examine the effect of different watershed vegetation and foliage.

To estimate the potential hazard to the population from the ingestion of fallout contaminated water it is necessary to determine the atom concentration in drinking water. The resultant body burden is calculated for different ingestion starting times and over different periods of consumption based on a consideration of physical, chemical, biological and physiological factors in their relation to water consumption and their interrelationship within the human body.

To perform computations on water contamination for selected water supplies as required by the sponsor to contribute to the OCD 5-city study, the previous methods of evaluation are being refined. Existing computer programs need to be streamlined to save valuable computer time and new computer programs for total atom concentration at any location from a single weapon and for multiple weapon attacks are being developed.

III. SCOPE

From the previous work it appeared that the degree of radioactive contamination from surface runoff, depending on environmental factors and especially watershed characteristics including hydrologic and physico-chemical aspects, may be a major factor in the rehabilitation and use of public water supplies.

Since empirical hydrologic expressions can not be applied directly to problems involving both hydrologic aspects and transport of activity, it was found that it is necessary to establisn relationships between hydrologic and physico-chemical pehnomena, such as ion exchange, diffusion, particle size, and other phenomena relevant to transport (2)(3)(4)(5) and to formulate these for quantitative use.

The fallout contamination of water supplies due to surface runoff during the postattack period may be evaluated by consideration of the following objectives:

A. Hydrology and Surface Runoff

This phase of the project essentially consists of a comprehensive delineation of the hydrologic cycle leading into methods of predicting runoff from rainfall and from antecedent conditions. It is necessary to closely examine the variables affecting runoff, such as: (a) slope, (b) ground roughness, (c) soil moisture, (d) antecedent rain, (e) terrain, (f) vegetation, (g) season, (h) soil composition and/or rock formation(s), (i) wind velocity and direction, (j) rainfall intensity, (k) rainfall frequency and duration and (l) watershed management and cultivation.

An analysis of these variables is necessary to obtain quantitative results of runoff for the various conditions that will be encountered postattack.

B. Chemical and Ion Exchange Properties of Fallout Nuclides

The solubility of radionuclides from fallout in surface runoff will be a major path of water contamination in the period after a nuclear war. When new ions from fallout particles are introduced into the soil, they compete with and replace other ions on exchange sites in the soil. In some reactions with the soil the new ions become nonexchangeable and thus some portion of the radioelement is rendered unavailable for uptake. Therefore, the types of interactions that occur between the soluble radionuclide and the soil constituents determine the availability of the radionuclide for uptake from the soil. Similar considerations enter the availability of a given radioelement for uptake by stream sediments and biota.

It is necessary to study the extent of surface penetration of radionuclides by natural processes and the extent to which cultivation practices determine the initial concentration in the soil, i.e. soil uptake contamination factor relationships (5). In addition, it is necessary to investigate the following:
(a) factors affecting the removal of various isotopes from different types of surfaces, including various soil covers, foliage, vegetation and crops,
(b) redistribution of various radionuclides alone or in chemical combinations

which may be expected following a nuclear attack and (c) ion-exchange properties and capacities of various soils, vegetation, stream sediment and biota to predict the retention behavior of radionuclides.

Although results are not always comparable, available data indicate that the phenomena of ion-exchange, chemical properties, uptake by biota and particle size exert considerable influence on the amount of nuclides ultimately available for surface transport by runoff.

C. Transport of Nuclide Activity

To calculate the effect of surface runoff on contamination it is necessary to know the soluble fraction of the activity of each biologically important nuclide. A study on the purely theoretical aspects of the problem of activity transport, in conjunction with ion-exchange, retention by solids, uptake by biota and redistribution phenomena has been initiated. As a mathematical transport model can be established, problems of uptake, ion-exchange and redistribution may then be superimposed to yield the ultimately desired results.

To analyze the transport problem it is necessary to examine available information in (a) activity transport by streams, including tracer studies (6) and sediment transport (2)(4), (b) overland transport, including surface transport (7) and (c) mixing of activity in reservoirs (6).

The analysis of the redistribution problem is expected to result in a mathematical model employing partial differential equations. The transport of activity by stream flow involves the theory of turbulent diffusion. As water from watershed runoff and streamflow approaches a reservoir or other area of surface storage, the initially deposited radioactivity undergoes diffusion. The boundary value problems of combined subsurface & overland flow, uptake of activity by soil and transport of activity by streams should be programmed for digital computer solution.

D. Estimation of Absorbed Dose

Following the evaluation of the concentration of water contamination from surface runoff, the potential short and long term hazards and radiobiological effects will be estimated. In connection with this analysis, the specific methods of calculating contamination levels will be reviewed and wherever possible the previous methods of evaluation refined.

To evaluate water contamination due to surface blasts of 5, 10 and 20 MT an arduous procedure had been followed. The difficulty was due to the lack of a successful computer program to evaluate nuclide solubility contour ratios. By incorporating the recently made available contour ratio values (N/I) into the existing program for intensity evaluation (I), the number of soluble atoms per sq ft (N) are found directly. This interpolation subroutine for computing the atoms/sq ft, N, directly will involve modifications of the program entitled "Estimated Intensity at Any Location in the Fallout Region for a Single Weapon Yield" (8). The program for multiple weapon yields will be modified similarly; it will give a read-out in atoms per unit area. The multiple weapon program previously presented (1), while efficient for two weapons, has proven to be quite uneconomical and too complicated for the poly-weapon situation. In

addition only the total intensity at a point was calculated. The new multiple weapon program is expected to give the total atom concentration for the entire watershed as well as for any point within the area of the attack. This latter output will be of special value to the evaluation of contamination due to runoff. For these reasons, a more sophisticated program is required for our specific needs and is currently under development. The new program will employ various subroutines and reserve the MAIN program for direct computation and summation of atoms per unit area.

With the aid of these computer programs it will be possible to estimate the absorbed dose in the human body over different periods of water consumption from a single surface burst and to maximize the contamination level due to several bursts and saturation raids.

IV. HYDROLOGY AND SURFACE RUNOFF

A. Introduction

The science of hydrology treats the behavior of water in the atmosphere, on the ground and underground. Although always important to the survival of man, it is only in comparatively recent years that attempts have been made to improve the empirical relationships which have governed this field. One of the primary aims of the science of hydrology has been the study of the relationship between rainfall and runoff.

In the previous report (1) the contribution of fallout on the watershed to water supply contamination was estimated by the use of an approximate runoff coefficient in the so-called Rational Formula, $Q = CiA$, for runoff. This estimate was used because it was not possible to investigate the problem to any greater depth in the time available. However, the estimate indicated that this contribution to contamination, namely, the amount brought into the water supply by surface runoff following a rainstorm, may in some instances be the largest contribution to the contamination.

The central purpose of this project is to improve the reliability of the estimate of the water supply contamination brought into the water supply by surface runoff. The physical phenomena that are relevant to surface runoff are so complex that little far reaching theoretical work has appeared in the literature. In fact, even the transport equation for water in a defined channel has been solved analytically for only a few special cases (2).

The field of hydrology has been confined for the most part to empirical relations with "coefficients" and "capacities", some of which are not well defined insofar that the definition leads to a means of measuring the quantity. Furthermore, the relevant parameters are not always explained with the presentation of data.

The hydrologic cycle, the movement of water as it relates to the earth, is an extremely complex system. To solve the problem of contamination from surface runoff requires a knowledge of (a) the fraction of activity due to specific radionuclides which are soluble in the runoff, (b) the speed with which the soluble portion of the activity may be transported overland by runoff to streams, lakes and reservoirs, and (c) the exchange reactions and other physico-chemical phenomena that affect the amount of activity that will actually reach the water supply. A series of modified transport equations may be ultimately used to solve this problem analytically. However, before any part of the overall problem can be solved it will be necessary to understand the dynamic behavior of the hydrologic cycle, in particular the runoff phase, in order that one prediction of the amount of runoff from a particular storm may be possible.

B. Fixed Limits of the Hydrologic Cycle

The oceans contain 97% of all the water in the world, or one quadrillion (10^{15}) acre-feet. The total amount of fresh water on the other hand is

estimated at 33 trillion (33×10^{12}) acre-feet. It is distributed roughly as shown in Table I.

TABLE I

Worldwide Distribution of Fresh Water

Source	Quantity (%)
Polar ice and glaciers	75
Ground water	
At depths < 2,500 ft	11
At depths > 2,500 ft, but < 12,500 ft	14
Lakes	0.3
Rivers	0.03
Soil (moisture)	0.06
Atmosphere	0.035

These are estimates of a static relation, and whereas the water content of the atmosphere is relatively small at any given time, immense quantities of water pass through it annually (9). For example, the annual precipitation on land surfaces alone is 7.7 times as great as the moisture contained in the entire atmosphere at any one time; that is, about 30 times as great as the moisture in the air over the land (10).

As can be seen from the figures above, an understanding of the "flow" nature of the cycle is necessary to appreciate the tremendous quantities of water in transit through the atmospheric and continental phases of the cycle.

C. The Hydrologic Cycle

Due to the complexity of the hydrologic cycle, water particles may be considered as following one of three paths. Of the water that reaches the land surface by precipitation, some may evaporate where it falls, some may infiltrate into the soil, and some may run-off overland to evaporate or infiltrate elsewhere or to enter streams (11). The larger part of the water falling on the land surface passes back to the air, either directly by evaporation or through the bodies of animals and plants in respiration and in transpiration. This evapo-transpiration accounts for 71% of the five billion acre-feet of rainfall that fall over the continental United States each year.

A smaller portion, the remaining 29% of the water reaching the land surface runs off and either sinks into the ground or stays on the surface until gathered by rivers that carry it back to the sea. Of the water that infiltrates into the ground, some may be evaporated, some may be absorbed by plant roots and then transpired, and some may percolate downward to ground water reservoirs (12). Water from these underground reservoirs may move laterally until it is close enough to the surface to be subject to evaporation or transpiration, some may reach the land surface and form springs, seeps, or lakes, and some may flow directly into streams or into the oceans.

Of the water that remains on the surface, some may accumulate in lakes and surface reservoirs, some may be lost through evaporation or transpiration or riparian vegetation, some may seep downward into ground water reservoirs, and some may continue on to a saline lake or to the ocean (11). A very small fraction is taken up in the bodies of plants and animals. Plants use its contained hydrogen in forming their tissues. The hydrogen is later recombined with oxygen through animal and plant respiration; the water thus produced returning to the air. The hydrologic cycle is completed by evaporation from the earth's saline water bodies and circulation of water vapor in the atmosphere.

D. Hydrologic Disposition of Precipitation

Rain and snowmelt seep into underground water-bearing strata (aquifers) and run off saturated-soil surfaces into streams, lakes, and rivers. Of this total precipitation, 70 to 75% is returned to the atmosphere by evapotranspiration from plants and vegetation, and by direct evaporation from moist soils, lakes and streams. This water is not available for man's volitional use. Slightly more than half of it is beneficial, however, as it sustains the growth of forests, grasslands and non-irrigated farmlands. The portion of precipitation that seeps into underground aquifers is particularly important, because the gradual overflow from full aquifers accounts for most of the regular streamflow (as distinct from that resulting from surface runoff).

1. Precipitation

Precipitation results when water vapor in the atmosphere is cooled sufficiently for some of the moisture to condense on dust particles or other condensation nuclides to form water droplets. Natural cooling of air masses results from (a) solar radiation or (b) lifting. Cooling by radiation - the cause of dew and frost - is relatively unimportant. However, cooling by lifting is the primary cause of precipitation, and may result (a) from topographic conditions, (b) from the convergence of weather fronts, or (c) from thermal convection.

In this discussion precipitation was assumed to be rain falling on unfrozen ground. The presence of snow, ice, or frost may have a great effect on the disposition of water in the hydrologic cycle. Interception losses may be much greater if the precipitation is snow. Evaporation losses from snow surfaces may also be very rapid. Much water may be stored temporarily on the ground until released by melt or evaporation. Frost in the ground may either increase or decrease the infiltration capacity, depending on the moisture content of the soil; a frozen soil with high moisture content may approach impermeability. A thick blanket of snow will prevent freezing in the ground, and snow-melt at the soil surface may keep the soil near saturation.

Freshly fallen snow is relatively "dry", i.e., of low density. The absorption of heat, even at temperatures below freezing, increases the density. Snow-melt is insignificant until maximum density is reached, then additional heat causes relatively rapid melting. Considerable rainfall can be absorbed by dry snow, but even a small amount of rain when the snow is close to maximum density, may result in complete snow-melt and in runoff exceeding the precipitation.

The rate of melting is proportional to the heat absorbed and, for this reason, is a gradual process unless hastened by rain. Although the ultimate disposition of snow-melt is similar to that for rain, the initial losses of rainstorms, consisting of interception, wetting of surface, and depression storage, are not so important in snow-melting.

2. Interception

Precipitation may be retained in foliage and evaporated or it may temporarily collect on leaves or needles, then drip or run down stems or crowns to the ground. That which is caught in the foliage and evaporated contributed nothing to water yields. The amount intercepted depends largely upon intensity, amount, and kind of precipitation and the density, type and height of vegetation.

Interception losses are greatest for areas of coniferous forest in winter, but rain interception may be appreciable for any type of vegetation, including grasses. The degree of interception differs according to whether the vegetation is coniferous, broadleaved, evergreen, or deciduous, has large or small crowns, short or long branches and rough or smooth bark. A light shower may be almost entirely intercepted. As the amount which can be held by leaf surfaces is limited, interception becomes less important with prolonged or heavy rains. Thus, only a small proportion of a heavy rain is intercepted; while snow is more readily held than any other form of precipitation.

Evaporation from leaf and other surfaces of vegetation probably is slight during a storm, because of a high relative humidity, but most interception loss is evaporated within a short period after precipitation ends. Practically no moisture is absorbed by plants from wet leaf surfaces; the immediate cooling effect of a summer shower on vegetation is generally caused by a reduction in transpiration rate.

Interception losses range from nearly 100% for light showers to about 25% for heavy rains. The total annual interception over the United States has been estimated as high as 40% of the annual precipitation in mature stands of coniferous forests and 15% of the annual precipitation as a general average for all forests (13). However, conditions vary so greatly even in small areas that general quantitative statements are of questionable value.

3. Infiltration and Percolation

Precipitation may (a) fall on a water surface, (b) be intercepted by vegetation, or (c) fall directly on the soil. A particle of water reaching the soil may (a) be returned directly to the sky by evaporation, (b) flow overland toward a stream, or (c) enter the ground by infiltration. The process of water entering the soil is called infiltration, and the movement of water to deeper depths in the soil is called percolation. More specifically, percolation is the movement of water under hydrostatic pressure through a rock or soil, excluding turbulent flow through large openings (14).

Evaporation from land or water surfaces during a storm is small and surface runoff does not begin until the soil surface is thoroughly wet and shallow depressions are filled; infiltration, however, begins with the first drops of rain. Water entering the soil first replenishes moisture deficiencies in the soil, and then contributes to streamflow and ground-water supplies.

Infiltration is determined by conditions at the immediate surface, whereas percolation is controlled by subsurface conditions; the rate of both often begins relatively high and decreases to a much lower and more or less constant rate as the rain continues. Molecular attraction is effective in pulling water into the soil until the upper part of the soil becomes wet. However, after this occurs, gravity is the principal force at work, and infiltration becomes a function of the permeability of the soil. Consequently, soils having coarse texture or of large aggregates, a layer of litter and humus on the surface, insects and small animals working in the soil and abundant roots of vegetation to make spaces for water movement and storage, have high infiltration and percolation rates. Other conditions that may cause variations of infiltration capacity are: (a) soil moisture content; (b) state of cultivation; (c) perforations of the surface soil and subsoil, such as those left by earthworms and decayed roots; (d) packing of the soil surface and the clogging of the soil pores by fine particles washed down from the surface by rain; (e) temperature changes; (f) shrinking and swelling of surface soils, including sun-checking during dry periods; and (g) depth to less permeable strata (14).

Since many of the above factors cannot be duplicated in the laboratory, it is usually necessary to measure the infiltration capacity of soils in place. Among the methods are the following: (a) measurement of the rate of intake of water on very small areas bounded by metal rings or tubes; (b) measurement of the rate of intake of water in areas artifically flooded by irrigation; (c) measurement of runoff of water applied to small areas by rainfall simulators; (d) comparisons of measured precipitation with measured surface runoff; (e) lysimeter studies; and (f) detailed measurements of soil moisture content at various depths.

Soil, or field moisture, is the moisture held by the soil close to the surface of the ground, usually within about three feet. Field moisture is held by capillarity, i.e. trapped between soil grains or held in colloidal gels far above the zone of capillary water that overlies the water table. This moisture supports most plant life and permits biological activities in the topsoil to continue by acting as a storage reservoir, replenished during rain and drawn upon during dry spells.

The most important factor that affects infiltration is the condition of the soil pores. Soil structure, especially near the surface, is extremely variable because so many different things act to change it. The most stable soils are sands, which support little plant life, and which undergo little change with the addition of water. Less stable are clays whose colloidal constituents swell with the addition of water.

The range of infiltration capacities for various soils has been found to be quite large, and quantitative measurements are applicable only to the soils and conditions at the time of measurement. Initial infiltration capacities may exceed 10 in./hr. and the ultimate or nearly constant capacity reached toward the end of a rain may approach or reach zero. Initial capacities are difficult to estimate, as the capacity usually drops rapidly after rain starts. The ultimate capacities may be measured more accurately but may vary considerably, even for the same soil.

Horton (15) introduced the concept of infiltration, defining infiltration capacity, f, as the maximum rate at which a soil in any given condition is capable of absorbing water. One of the most striking characteristics of infiltration capacity is its extreme variability with respect to both area and time. At the beginning of any storm the infiltration capacity, f_o, is likely to be high; it then decreases rapidly during the first hour or so and finally levels off and approaches a constant value, f_c, after the next hour or two. The ratio of f_o to f_c depends greatly upon permeability. For a well-compacted clay it is high, and for a coarse, sandy soil it is relatively low. This characteristic may be more readily understood when it is realized that the infiltration capacity of any particular area is determined at the ground surface, ordinarily it is the nature of the openings that exist in the top $\frac{1}{4}$ in. of the soil that determines infiltration capacity. However, where subsurface storm flow occurs it is the condition of the surface layers of the relatively impervious strata which determines the infiltration capacity. Inasmuch as in all cases f is dependent upon the character and condition of this layer, it is readily understandable that any disturbance of that layer may completely change the infiltration capacity. From all this it appears that infiltration capacity is not a permanent characteristic of a watershed that is comparable with size, length, and similar fixed properties. Instead, where the objective is the determination of surface runoff, it is necessary to determine the range within which the average infiltration capacity of a basin varies from time to time; then knowing the factors that cause those variations and knowing the influence of each, estimate the value that should prevail at any given time. Thus, with the minimum, maximum, or average infiltration capacity existing during any design storm, it is possible to determine the greatest, smallest, or average runoff that will result from such a storm.

The typical infiltration-capacity curve starts with a high value, f_o, because of the initial soil conditions, then dropping rapidly during the early stages of the storm and finally levelling off and approaching a constant value, f_c. For different watersheds this ratio, f_o/f_c, has a wide range, depending on the amount of interception and depression storage, the type, texture and condition of the soil as previously mentioned. Horton (16) suggested that it would decrease exponentially with time during a storm and approach a constant rate, usually after a period of 1 to 3 hr. and that it may be represented by an equation of the form:

$$f = f_c + (f_o - f_c)e^{-kt} \qquad (1)$$

where:

f = infiltration capacity at any time (inches/hour)

f_c = constant, or ultimate, infiltration capacity (inches/hour)

f_o = initial infiltration capacity (inches/hour)

e = Napierian base

k = a decay constant for a given curve

t = time from the beginning of precipitation (hours)

Attention should be called to the fact that the infiltration-capacity curve is, in practice, not an f curve but, rather, it is an average infiltration capacity, f_a, curve. In other words it does not represent instantaneous values of infiltration capacity as it existed throughout the storm period, but instead it represents the average infiltration capacity for each of the several periods of high storm intensity. The infiltration approach to runoff is based on the use of infiltration indices. The Φ-index, for example, is the average rainfall intensity above which the total mass of rain equals the total mass of the observed runoff. The remainder of the total precipitation consists of gross basin recharge, i.e. surface retention plus infiltration. Another concept, the W-index, has been defined as the average rate of infiltration, usually measured in inches depth per hour for a given area, during the time rainfall intensity exceeds infiltration capacity:

$$W = \frac{F_i}{T} = \frac{1}{T}(P - Q_S - S_e) \qquad (2)$$

where: W = average rate of infiltration, when rainfall intensity exceeds infiltration capacity (inches/hour)

F_i = total amount of infiltration (inches)

T = time during which rainfall intensity exceeds infiltration capacity (hours)

P = precipitation (inches)

Q_S = observed surface runoff from the storm (inches)

S_e = total surface retention (inches)

This approach has been successful in estimating maximum flood flows which consist almost entirely of surface runoff, when the initial moisture condition of the soil is quite uniform. The W-index is estimated and an infiltration curve superimposed on the rainfall plot. The surface retention is then estimated and added to the infiltration curve. The surface runoff is represented by the area between the rainfall curve and the infiltration plus surface retention curve (17).

4. Surface Runoff and Subsurface Storm Flow

As long as the rate at which rainfall reaches the soil surface is less than the infiltration capacity, all the available supply of water sinks into the soil. As rain continues, plant surfaces become saturated, the interception-loss rate declines, and the infiltration capacity also decreases. Whenever the supply rate of rain exceeds the infiltration capacity, shallow depressions begin to fill with water, and when these depressions are filled to overflow level, water begins to move by overland flow toward streams. Overland flow usually reaches a tiny rivulet or channel within a short distance. The time of travel from raindrop to stream channel depends on distance, slopes, and surface conditions and may also be affected by depth of flow. Generally the time of travel is a matter of minutes.

"Surface runoff" is the water which reaches a stream by overland flow and is a residual equal to precipitation minus the total evapo-transpiration losses and the total ground-water flow. It can be directly measured on small sample plots and on ephemeral streams, but on larger streams the hydrograph of streamflow is complicated by ground-water inflow and channel storage. In this area, the analysis and synthesis of the hydrograph is one of the fundamental problems of stream hydrology.

A division does not take place at the soil surface between soil moisture and surface runoff. As indicated above, not all overland flow reaches a stream channel - thus, the distinction between overland flow and surface runoff. This water which flows through the soil but above the water table, is called "subsurface storm flow." Under some conditions, when a relatively impermeable layer retards or prevents the percolation of water downward and diverts it back to the surface or into stream channels, subsurface storm flow may reach stream channels almost as rapidly as does overland flow. However, if the soil above the water table becomes saturated, it constitutes a temporary or perched water table and may contribute a substantial amount of water to streamflow during or after a storm. A sharp division between surface runoff and ground-water seepage flow is therefore, impossible.

5. Streamflow

Streamflow is measured by recording the stage or elevation of the water surface at a given station. The actual average flow velocity in the cross-section at the station is measured with a current meter for a number of flow conditions at different stages. These values are used to get a stage-discharge relationship, or rating curve. The discharge Q is computed as:

$$Q = \Sigma A_1 v_1$$

where: A_1 = cross-sectional area of the part of a stream at a gaging station, and

V_1 = average velocity in that part of the stream.

The average velocity, V, of the stream at a station therefore is:

$$V = \frac{\Sigma A_1 v_1}{\Sigma A_1} \qquad (3)$$

The discharge may be determined by the slope of the energy line (approximated by the slope of the water surface) as follows:

$$Q = \frac{1.49}{n} A R^{2/3} S^{1/2}$$

where: Q = discharge (cfs)

A = cross-sectional area of flow (sq ft)

R = hydraulic radius: ratio of A to contact line of A with river bed and banks

S = slope

n = Mannings roughness coefficient

For two discharges at the same station and stage:

$$\frac{Q}{Q_o} = \left(\frac{S}{S_o}\right)^{1/2} \qquad (4)$$

6. Transpiration

The biological sciences of botany, ecology, and plant physiology are all concerned with this phase of the hydrologic cycle. Plants absorb water, principally through their roots, use the water in several involved ways in their physiologic processes, and give off water to the atmosphere largely through water-vapor diffusion through the pores or stomata in the process called "transpiration". The amount of water held in storage by a plant is less than 1% of that lost by it during the growing season (14). Therefore, from the hydrologic standpoint plants are pumps which remove water from the ground and raise it to the atmosphere.

In some areas where seasonal drought is usual, the amount of water removed from the soil by transpiring plants depends largely upon the depth of root penetration. However, since transpiration is essentially a process of evaporation, it depends largely on the same factors that influence evaporation from land and water surfaces - namely, solar radiation, temperature, wind, and relative humidity.

Although numerous experimental methods of determining transpiration rates have been developed, their general applicability to hydrologic studies is varied, since many of them were developed for the study of specific problems. One method consists of weighing freshly cut parts of plants, immediately after cutting and periodically thereafter until wilting starts. It is based on the assumption that transpiration continues at the normal rate immediately after cutting. Another method is by potometer measurements. A potometer is a vessel containing water into which the cut end of a plant or leaf is inserted. After sealing, measurements are made of the amount of water removed from the vessel. A third method is by phytometers. These differ from potometers, in that they contain soil in which the whole plant is grown, thus approaching natural conditions. The closed phytometer is used extensively.

The quantity of water involved in the transpiration process is important as can be seen from the following: "An acre of corn gives off about 3,000 to 4,000 gallons of water each day while a large oak tree gives off about 40,000 gallons per year" (18).

7. Evaporation

Evaporation from soil surfaces varies roughly in the same manner as does transpiration and usually can not be separated from transpiration losses. Soil evaporation rates vary within wide limits, from approximately the maximum rate for free-water surfaces to zero (14). Vegetation shades the soil and reduces the soil evaporation, but transpiration usually exceeds this reduction, so that plants increase the total losses.

Because of the nearly insurmountable difficulties of making separate measurements of the two phenomena, evaporation and transpiration are generally lumped as "evapo-transpiration." If we neglect storage in the soil moisture and in ground water, then the difference between total precipitation and total stream flow is the total evapo-transpiration.

The measurement of evaporation from free water surfaces by "direct means" requires the measurement of all inflow, outflow, and storage, with the difference assumed to be evaporation. There are few natural water surfaces for which evaporation losses can be adequately measured by this method.

There are several approaches to indirect measurement of evaporation, but the various factors affecting it are difficult to estimate. Some of these factors are temperature of the air and water, differences in vapor pressure, humidity of the air, solar radiation, wind movement, barometric pressure, and chemical quality of the water.

The maximum possible evaporation rate has been given by Meyer (19):

$$\frac{dE}{dt} = C\ (e_s - e_a)\ (1 + \frac{W}{10}) \qquad (5)$$

where:

$\frac{dE}{dt}$ = maximum evaporation rate (inches/day)

e_s = saturation vapor pressure (mb or in. of Hg)

e_a = existing vapor pressure in air (mb or in. of Hg)

W = wind velocity about 25 ft. above the surface (mph)

C = a numerical coefficient ranging from 0.36 for ordinary lakes of about 25 ft. depth to 0.50 for wet soil surfaces, small puddles and shallow evaporation pans.

Barometric pressure has only a small effect on evaporation. A drop of the barometric pressure from 30 in. to 20 in. increases the evaporation rate by 20%.

Water pollution decreases the rate in proportion to the percentage of dissolved solids, i.e., sea water with 35,000 ppm of total solids (96.5% water) evaporates 96.5% as rapidly as fresh water.

When considering evaporation from land, the availability of the water is a factor. Evaporation opportunity is 100% for lakes and streams.

a. Reservoir Evaporation

The principle of conservation of mass as expressed in the water budget equation may be used to determine evaporation from a reservoir:

$$P + I = E + \frac{\Delta S}{A_{av}} + O \qquad (6)$$

where: P = precipitation on reservoir

I = inflow

O = outflow

E = evaporation

$\frac{\Delta S}{A_{av}}$ = change in storage per unit area of the reservoir.

This equation applies either instantaneously in which case the qualities are to be considered rates or over a given period of time in which case the quantities are to be considered accumulated totals. There may be a large error in the measurement of evaporation by this method, especially over a short period of time, due to the inherent difficulty in measuring the subsurface components of I and O.

The most common method is by means of evaporation pans after establishing a relationship between pan evaporation and reservoir evaporation.

If the net evaporation is greater than precipitation, streamflow always decreases as a result of the construction of a reservoir, and usually, but not necessarily vice-versa (17).

b. Monthly Evaporation

A graphical relationship may be developed, similar to Meyer's equation for daily evaporation, to give monthly evaporation (20), as follows:

$$E = (7.8 + 0.32\ v_w)\ (e_s - e_a) \qquad (7)$$

where: E = monthly evaporation (inches)

v_w = wind velocity (mph)

e_s = saturation vapor pressure (inches of Hg)

e_a = actual vapor pressure (inches of Hg)

E. Hydrographs

The hydrograph is a plot of discharge or runoff as a function of time. The study of the hydrograph of a river before, during and after a storm is useful in determining how much of the storm precipitation reaches the river as direct surface runoff or storm runoff. The study of the hydrographs of a series of storms of various durations and under different conditions is a first step in establishing a rainfall-runoff relation for a given basin.

1. Hydrograph Composition

The four components of runoff are surface runoff, interflow, groundwater flow and channel precipitation. The most relevant parameters and their influence on these four components of runoff are: rainfall intensity

and duration, infiltration rate and volume, and soil moisture deficiency. Generally speaking, four different shapes of hydrographs occur depending on the relative magnitude of these parameters:

Case I: Rainfall intensity, $i <$ infiltration rate, f_i, and volume of infiltrated water, $F_i <$ soil moisture deficiency

Because of the second assumption, there will be no contribution to runoff from either interflow or ground water flow from this storm. Because of the first assumption, there will be no surface runoff. Therefore the only runoff contribution will be that due to rainfall directly on the stream (channel precipitation). The hydrograph for this case will show only a slight increase of the discharge with respect to time over the expected base flow.

Case II: Rainfall intensity, $i <$ infiltration rate, f_i, and infiltration volume, $F_i >$ soil moisture deficiency

In this case, after soil moisture has reached its maximum value, there is an additional contribution of interflow and ground-water flow to streamflow.

Case III: Rainfall intensity, $i >$ infiltration rate, f_i, and infiltration volume, $F_i <$ soil moisture deficiency

In this case there are contributions to streamflow from surface runoff and from channel precipitation, but, due to the second assumption, no additional contribution to the existing base flow from interflow or ground-water flow.

Case IV: Rainfall intensity, $i >$ infiltration rate, f_i, and infiltration volume, $F_i >$ soil moisture deficiency

This is the general case of a big hydrologic storm. There is additional streamflow due to contributions from all four components of runoff; i.e. channel precipitation, surface runoff, interflow, and ground-water flow. The hydrograph for this case is shown in Figure 1.

2. Separation of Hydrograph Components

The problem for a given hydrograph is how to separate the various components of stream flow and particularly to determine how much is due to surface runoff. To simplify the problem in practice, the contributions due to channel precipitation and interflow are included in surface runoff as a single item and referred to as direct or storm runoff. This procedure is somewhat unfortunate for estimating contamination, but acceptable for the design case, since almost all of the storm runoff will be surface runoff anyway. Figure 1 is a typical big storm hydrograph. In it the various contributions to runoff are indicated: (a) surface runoff; (b) interflow; (c) ground-water flow; and (d) channel precipitation. The parts of a hydrograph are also indicated, the rising limb or concentration curve, the crest segment and the recession or falling limb. The time base, T, of a

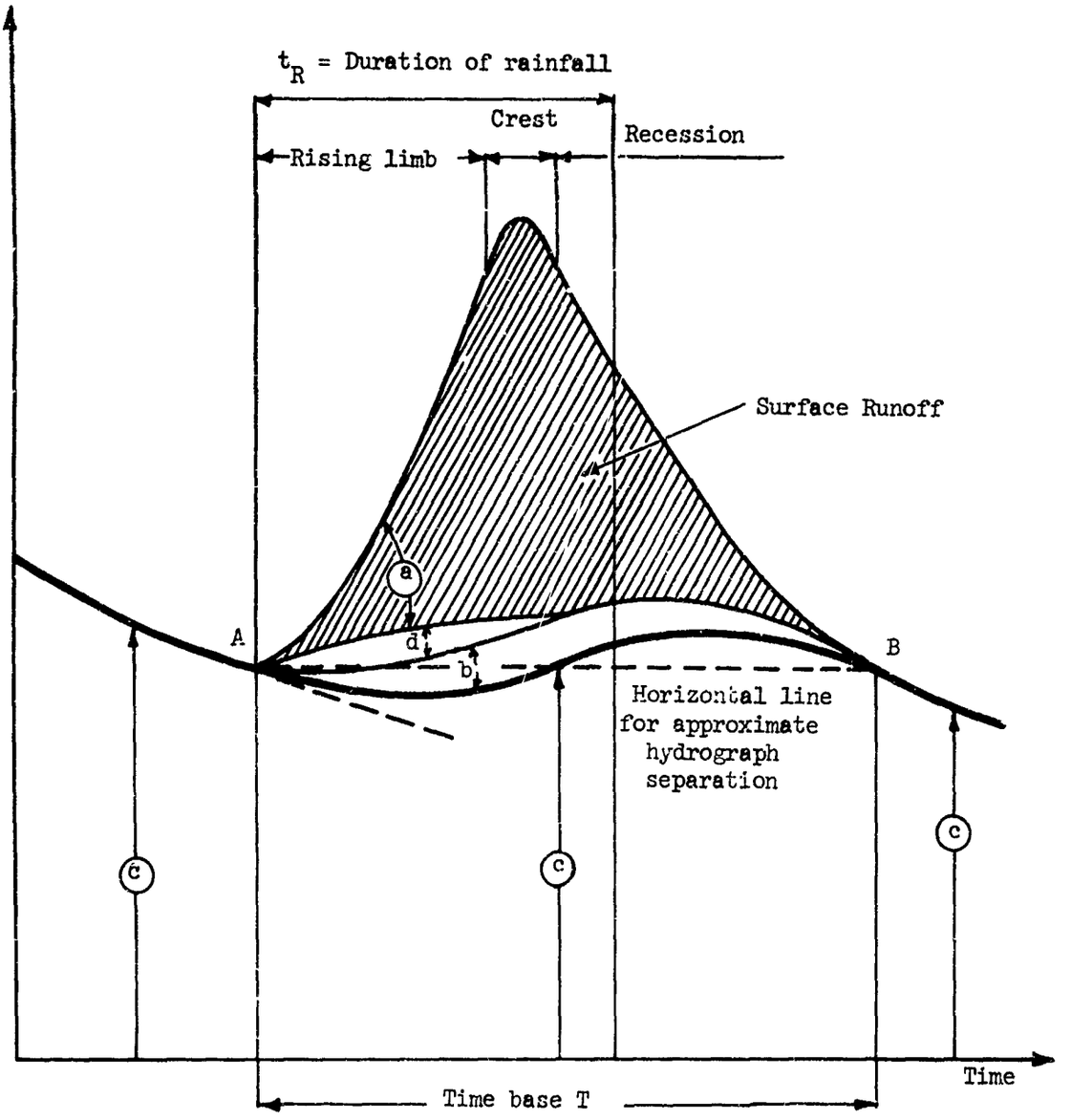


Figure 1. Hydrograph for a Large Storm, Showing also Flow Contributions of the Various Components (after DeWiest (17))

hydrograph is obtained by drawing a horizontal line from the point A, where the rising limb begins to its point of intersection B with the recession curve. This horizontal line may also be considered, as a first approximation, to be the boundary between base flow (ground water flow) and storm runoff.

There are more sophisticated methods (17)(21) to separate these components of runoff but they consist mainly of various methods of curve fitting.

3. Shape of the Hydrograph

The shape of the storm hydrograph, in particular the rising limb, crest and early recession, is determined essentially by surface runoff. It is a function of such storm characteristics as duration, areal distribution, intensity variation of rainfall and also the shape of the basin.

The time base of the hydrograph, T, is the time from the beginning of the rising limb to the time on the hydrograph when direct (or storm) runoff is practically zero. According to Sherman (22) the time bases of all hydrographs for a given basin and for storms of the same duration are equal. This assertion formed the basis for the unit hydrograph. The time base, T, may be defined by:

$$T = t_R + t_c \tag{8}$$

where: t_R = duration of the storm

t_c = time of concentration for the drainage basin (the time required for water to travel from the farthest point of the basin to the outlet point.)

The effect of non-uniform areal distribution of rainfall is marked by a flat slope of the rising limb if most of the rainfall occurs in the region most remote from the basin outlet, and by a steep, rapid rise of the concentration curve when most of the precipitation occurs near the outlet. If the intensity of rainfall varies there may be more than one peak in the resulting hydrograph. The shape of the basin will affect the shape of the hydrograph; i.e. if most of the area is concentrated near the outlet, the peak of the hydrograph will be sooner (rapid rise), if most of the area is away from the outlet, the peak will be later (slow rising hydrograph).

4. Rainfall - Runoff Relations

The relation of runoff to rainfall is affected by so great a number of factors that it is obvious that no single relationship can be established to predict the runoff from a storm of given rainfall and duration (17). Nevertheless, for many years the rational approach to runoff was the use of dimensionless runoff coefficients to estimate runoff as a certain percentage of rainfall. In these methods allowance was even made to subtract from the data that portion of the rainfall below which there was no runoff. Other attempts have employed the method of least squares to fit quadratic equations to relate rainfall to runoff. The rational approach has some merit in the analysis of impervious areas such as parking lots and airport pavements.

However, for natural soil conditions, it seems logical to group the data according to the condition of the soil before the storm and to establish curves of runoff versus rainfall for each soil condition.

5. Initial Moisture Conditions

Several indicators of initial moisture conditions have been used: initial ground-water flow, soil moisture deficiency, pan evaporation data, total precipitation before storm. Employing the concept that soil moisture should decrease logarithmically with time during periods of no rain, Kohler and Linsley (23) devised the antecedent-precipitation index, API, which attaches a numerical value to the moisture conditions of the soil before a storm. They proposed the equation:

$$I_t = I_o k^t \qquad (9)$$

where: I_o = the initial value of API (inches of water)

I_t = the reduced value t days later (inches of water), and

k = a recession constant, varying from 0.85 to 0.98

6. Unit Hydrograph

The concept of the unit hydrograph for a storm of a given duration for a specific basin was introduced by Sherman (22). It is based on the fact that the time of concentration, t_c, is a constant for a basin and therefore the time base, $T = t_c + t_R$, is the same for all storms of the same duration for a given basin. The shape of the unit graph is obtained by averaging the characteristics of many storms (on a specific basin) of the same duration. The area under the unit graph represents one inch of direct runoff from the basin. The hydrograph for any storm of the same duration is obtained from the unit graph by multiplying the ordinates of the unit graph by the storm runoff. Therefore, the unit hydrograph is also useful to predict peak flows.

The above method is for storms of fairly uniform rainfall intensity and is limited to one-peak hydrographs. In the case of a complex storm with several peaks it may be possible to divide the storm into a number of individual hydrographs, each of which is obtained from a unit graph (17).

Attempts have also been made at constructing the unit graph for storms of one duration from the graph for storms of a different duration. One such case is the following: Consider a storm of duration $2t_R$ to be made up of two storms each of duration t_R. Shift one graph for this storm (this is the known unit graph) by t_R along the time base relative to the other and add ordinates. The resulting graph is for two inches of runoff, therefore, dividing these ordinates by two gives a unit graph for a storm of duration $2t_R$.

In the absence of streamflow data for a particular basin, a method has been used by Snyder (24) and others (17)(25) to construct synthetic unit graphs for the basin.

7. Frequency Analysis of Runoff Data

Another basic approach that has been used for the prediction of runoff is based on statistical analysis of runoff data. The assumption is that a discharge of Q (cfs) would occur on the average once every N years. If it were decided that, say, a 100-year event would be sufficiently probable to take into consideration, the runoff corresponding to this probability would be the amount chosen to work with.

8. Rainfall Intensity - Duration - Frequency Curves

Since there are not many locations that have runoff data for periods long enough to avoid extensive extrapolation in the prediction of even a 100-yr. runoff event, appeal has sometimes been made to the usually much longer rainfall intensity - duration data available. This method assumes essentially that a 100-yr. rainfall event produces a 100-yr. runoff event. The previous discussion of the relation between rainfall and runoff should make clear the dangers inherent in this assumption.

F. Drainage Basin

The drainage basin or watershed, of a stream is that area that contributes runoff to the stream; it is the natural unit for many hydrological studies. The boundaries of a basin are divides or ridges which separate it from adjacent basins. A basin has a single outflow point, either where the stream cuts through a divide or where the stream reaches the ocean.

First of all, it is necessary to consider the physical characteristics of the basin itself or its morphology (26)(27). Some of the relevant characteristics are: (a) drainage area of the basin (the area contributing to runoff), A_d, and (b) drainage density (stream length in the basin. area) $D_d = \Sigma L/A_d$, where ΣL = total stream length in the basin. Values of D_d vary from less than 1 mile/sq. mile for a poorly-drained basin to about 5 mil/sq. mile for a well-drained basin.

Streams may be typed by their flow constancy as follows: (a) perennial (at all times above surface flow except during time of extreme drought), (b) intermittent (mostly above surface but sometimes dry due to evaporation and bank storage), and (c) ephemeral (from flash runoff or snowmelt only).

To compute the time distribution of runoff the distribution of area with distance from the outflow station is considered. On a basin map isopleths (lines of equal distance along streams from the outflow point of the basin) are drawn and the percentages of the drainage area beyond an isopleth versus the isopleth value in miles are plotted. This gives the distribution of drainage area as a function of distance from the outflow point.

Another distribution curve, a plot of elevation vs. area, may be constructed from a topographic map and is useful in comparing drainage basins. The curve is a plot of the average elevations vs. the areas in percentage of the total area. Either the median elevation, such that one-half of the area is above and one-half below, or the mean elevation, which is a weighted average, may be used.

The stream profile shows the elevation of the main bed of a stream as a function of its distance from the basin outflow point. The gross slope of a stream between any two points is the total fall between the points divided by the stream length. The mean slope is constructed by drawing a straight line such that the areas enclosed above and below the stream profile are equal. The stream profile and the mean slope are specific characteristics of the stream channel and are not suitable for use as parameters describing the slope of the overall basin. The average land slope of a basin may be determined by a method of superimposing grids over a topographic map according to Horton (28).

V. ION EXCHANGE IN SOILS

The interaction of fallout particles deposited on the watershed with the soil is of great importance in this study. The deposited nuclides that are dissolved by surface runoff may undergo ion exchange with the surface layers of the soil. Certain of the isotopes are held quite tightly by soils, such as cesium by clays and hence are not expected to appear in runoff. Others, such as strontium are generally not sorbed very strongly. Reports of relevant experimental work from the literature, are summarized in Section A of this Chapter.

A simplified mathematical model of uptake by soils is presented in Section B. This model has the virtue of providing an analytic solution. It is intended as a first approximation since it was derived for the case of isotopic exchange. Strictly speaking this case obtains rarely in practice. Equations incorporating more general ion exchange processes should be used. These equations entail much greater mathematical complexities and the analysis is deferred to a subsequent report.

It should further be noted that this model is restricted to a one-dimensional case and to moisture-saturated soil. In practice, the soil is not saturated during at least part of the period of infiltration. This model or a subsequent one, is to be incorporated into an analysis that will provide the overall picture of transport of radionuclides in overland flow and infiltration and will lead to an accurate description of the distribution of the activity between these two categories.

A. Literature Survey of Experimental Results

Many nuclides have a strong affinity for cation exchangers, such as clays and soils, and may be retained by the soil rather than removed by surface runoff. The amount actually removed by runoff depends on the chemical composition of the soil and the amount of organic matter it contains (29)(30)(31)(32)(33)(34). Reports in the literature generally agree that pH greatly affects nuclide sorption, with the best sorption occuring at the higher pH values, as illustrated by Table II for Savannah River Plant Soil, according to Prout (35):

TABLE II

Exchange Capacity of Soil (Savannah River Sediment)

pH	meq/100 g Soil	meq/100 g Clay
4	0.012	0.06
5	0.108	0.54
6	0.372	1.86
7	0.504	2.52
8	0.600	3.00
9	0.744	3.72
10	1.24	6.18

Results of studies conducted with the more common clay minerals show that they have different affinities for different nuclides (29)(35) (36-42). As presented by Lacy (43), most clays have preference for competing ions in the following order:

$$Ba^{++} > Sr^{++} > Ca^{++} > Mg^{++}$$

and

$$Cs^{+} > Rb^{+} > NH_4^{+} > K^{+} > Na^{+} > Li^{+}$$

Additional data on the cation exchange capacity of a number of clays (44) has been tabulated in Table III below.

TABLE III

Important Properties of Some Clay Minerals

Group and Lattice Type	Name	Cation exchange capacity (meq/100 g)	Approximate size range (μ)
KAOLINITE group (1:1 lattice)	kaolinite	3-15	0.5-2
	halloysite	40-50	0.04-0.2
MONTMORILLONITE group (2:1 expanding lattice)	montmorillonite	80-125	0.01-0.1
	beidellite	60-90	0.05-0.5
	nontronite	60-70	0.01-0.1
	saponite	20-30	0.01-0.1
ILLITE or HYDRATED MICA group (2:1 non-expanding lattice)	illite	20-40	-
	pyrophyllite	-	-

As the result of the initial literature survey, experimental data for specific cases have been summarized in Table IV, as shown on pages 25 and 26.

TABLE IV

Summary of Experimental Work on Ion Exchange Uptake in Soils (Sr and Cs)

Element	Soil	Results	Reference
Sr-90	(Los Alamos) tuff	Not tightly bound; easily replaceable	45
Sr	Savannah River Plant Soil	High H^+ strongly inhibits adsorption; Na^+ and NH_4^+ inhibit adsorption above a pH of 8; Ca^{2+} seriously inhibits adsorption; Na and Al compete with Sr for exchange sites but not as much as with Cs	35
Sr	Vermiculite	$(PO_4)^{3-}$ improved sorption of Sr when added in concentrations up to 100 ppm	36
Sr	Montmorillonite	Sorption reduced by the following ions in this order. $Ba^{2+} > Cs^{2+} > Mg^{2+} > H^+ > NH_4^+ > K^+ > Na^+$. Indicating that Montmorillonite sorbs Sr by ion exchange	36
Sr	Montmorillonite, vermiculite, variscite, Tenn. rock phosphate, Fla. pebble phosphate	Ca^{2+} increases sorption up to a concentration of 1000ppm	36
Sr	Coalinga, Dominguez, Lost Hills-Asbestos, Richfield, Rosecrans, Halloysite Clay-Asbestos, Yolo Soils-Asbestos	H^+ concentration had a marked effect e.g. reducing pH caused significant reductions in Sr uptake. Equilibrium constants were determined for Sr-Ca which was around 1.3. It was dependent on the H^+ concentration.	40
Sr	Rosecrans sand	With Na in the liquid phase Sr-Ca equilibrium constant was 1.79	40
Sr	Kaolinite, halloysite, montmorillonite, illite	The concentration of Ca decreased Sr sorption more than did Na concentration. Author concludes that to predict sorption of Sr by Clays it is necessary to consider Na-Ca ratio in the water as well as total cation concentration	46

TABLE IV (Cont'd)

Summary of Experimental Work on Ion Exchange Uptake in Soils (Sr and Cs)

Element	Soil	Results	Reference
Sr-90	World-wide soil distribution, geographically indexed	There was little downward movement of the Sr-90 through soils. It takes several years of heavy rainfall for Sr-90 to be moved even a few inches downward	47
Sr-90	Clay	97% of the Sr was removed by 50 ml of leachate when leached by 100 ml of H_2O and NH_4 acetate	48
Cs-137	(Los Alamos) tuff	Tightly bound	45
Cs	Savannah River Plant Soil	Decrease in adsorption at pH below 6 due to H^+; high pH decrease in adsorption due to Na^+	35
Cs	Clays	As Ca or Na concentration is increased, Cs sorption is decreased. The author concludes that as a first approximation the sorption of small quantities of Cs by clays would be dependent only on total cation concentration in the water	46
Cs-137	Clay	Only 51% removed in the first 50 ml of leachate when leached by 100 ml of H_2O and NH_4 acetate total activity of Cs-137 leached was $\frac{1}{4}$ that of Sr-90	48

B. Model for Uptake of Radioactivity by Runoff - Diffusion Into a Rod from a Solution of Finite Volume

The model, except for the finite volume of the solution, is quite analogous to sorption by clays. In the experiment, described by equation (10) below, a rod, initially free of radioactivity, is insulated except for one end which is exposed to a radioactive solution circulating rapidly past the rod. The decrease in activity of the solution $\bar{Q}/Q_o$, is given by:

$$\frac{\bar{Q}(t)}{Q_o} = e^{f^2} \operatorname{erfc}(f) \qquad (10)$$

where:

$f = \frac{\alpha A}{V} (Dt)^{\frac{1}{2}}$

A = cross-sectional area of rod (cm^2)

V = volume of solution (cm^3)

$\alpha = \frac{\bar{C}^*}{C^*}$

$\bar{C}^*$ = equilibrium concentration of radioactive species in solution $(\frac{ions}{cm^3})$

C^* = equilibrium concentration of radioactive species in the rod $(\frac{ions}{cm^3})$

It should be noted that in the model the amount of activity in the solution is initially fixed, while in the case of uptake by soil, the soild is continuously exposed to a constant concentration of radioactive solution.

Clearly the above model differs from the actual situation in uptake by soil from runoff in many aspects. The model does have the virtue of having an analytic solution. The authors intend this model only as a first approximation; the actual equations and boundary conditions for ion exchange (as distinct from isotopic exchange as considered in the model) should be solved numerically on a computer.

The strong analogy between the present problem and the operation of an ion-exchange column has also been noted.

VI. PLANT UPTAKE

A. General

In their course of travel before reaching a water source, fallout nuclides may also be taken up by the plant cover of the watershed. It is necessary to know the behavior of the various nuclides with respect to plant uptake, as this will affect the final amount of activity reaching water supplies.

Fallout nuclides may be taken up by plants in two ways:

(a) The may land directly on plant parts and be taken in through the leaves, or, (b) they may be taken up by the roots.

Nuclides which land on the plants may also be washed off the plant by rain and enter the water system by runoff. The uptake by plants, however, is important to estimate the total amount available for future runoff (37)(41)(42)(49). The composition of the soil has a distinct effect on plant uptake of nuclides (37)(38)(39)(50)(51)(52)(53)(54)(55).

B. Uptake of Sr-89, 90

Schulz, et al.(51) ran culture studies on plant uptake of Sr-90. They found greater uptake by the plant than extraction by water. They stated that conditions in the soil may be different than the culture and the amounts of Sr extracted may not be the amounts available to plants. Schulz, et al., also indicate that some reports have found Sr to be in unexchangeable forms which could be due to the type of soil and length of time Sr has been in the ground.

Libby (37) found that plants contain about twice the specific Sr-90 relative to Ca in soils on which they grew. This may be due to fallout on plant surfaces. Menzel, et al., (56) found that the Sr-90/Ca ratio of cowpeas was "approximately inversely proportional to the available Ca in the soil ..."

Various investigators have found that addition of Ca to soils as gypsum, or lime, decreased the Sr-89, 90 uptake, except in soils already calcareous (55). Nishita, et al. (30)(31), using various organic fertilizing materials, ran tests on Sr-90 uptake. Lettuce had the greatest effect with 10 gm lettuce/100 gm soil reducing the Sr-90 content by 20 to 40% of plants grown on soil with no addition. This decrease due to the addition of organic materials may be explained in several ways such as: Microbial activity, changes in composition and amount of soil air, decreasing the ratio of divalent to nonvalent cations, and the amounts of mineral nutrients being increased (55).

C. Cs-137 Uptake

Nishita, et al. (39), found the Cs-137 uptake was dependent on the potassium concentration. The greater the potassium concentration in the soil the less Cs-137 was taken up. The addition of small amounts of non-radioactive Cs-137 greatly increased the uptake of Cs-137. The ratio of

Cs/K in uptake depended on the soil type. Handley, et al. (42), used a greater number of ions with the Cs-137 and found K, Rb, NH_4 and Cs had large effects on Cs-137 with K and Rb having the greatest deterring effect. Middleton, et al. (41), observed that barley absorbed K-42 to a greater extent than Cs-137 relative to the concentration of the external solution in the culture. Jackson, et al. (38), found that different salts had different effects. Some uptake results were quite different from those of Handley, et al. (42), who found Rb and NH_4 decreased Cs-137 uptake, while Jackson found the opposite as shown in Table V.

D. Comparison of Uptake

It has been found that plant uptake is in the following order: Sr-89, 90 >> I-131 > Ba-140 > Cs-137 and Ru-106. The uptake of Sr-89, 90 was from 0.5 to 5% of the amount in soil, while the other nuclides are taken up in smaller percentages (57)(58)(59).

Klechkozsky (60), using Sr-90, Ce-144 and Ru-106, observed that strontium uptake was reduced 20% when the soil was limed. This reduction was probably due to the fact that the solubilities of Ce and Ru were decreased with an increase of pH. The presence of NH_4NO_3 increased the uptake of all cations.

In several Russian experiments using Sr-89, 90, Ce-144 and Ru-106 it was found that uptake was decreased in all instances when lime and organic matter were added. Also, legumes take up the nuclides to a greater extent than do cereals. Strontium is taken up in the greatest amount by the plants and it is most radically reduced by the additives. In one experiment, when only organic matter was added, the decrease was greater than when only lime was added, but less than when both lime and organic matter were used (32)(33).

To determine if an increase of the sorptive capacity of the soil is caused by addition of lime and organic matter to the soil, Guliakin, et al., (32)(33) performed experiments in which one gram of soil was placed in a test tube to which 10 ml of a solution of measured radioactivity was added. The soil was shaken and centrifuged and the activity in the solution measured again. This was done again with salts, lime and organic matter added at various points of the experiment and in various combinations.

The results demonstrate that lime and organic matter had no marked effect on the amount of Sr, Ce, and Ru sorbed by the soil. There is a reduction in the displacement of Sr-89, 90 and Ce-144 from the absorbed state when lime or organic matter is introduced into the soil even by calcium and potassium salt. The salts displaced almost no absorbed Ru-106 even when lime and organic matter were introduced into the soil. Ru-106 was reduced in plants whose soil had been treated with lime and organic matter. It may be concluded from these observations that a plant has greater sensitivity to a change in nuclide sorption than shown by these experiments (32).

Another experiment seemed to indicate that plant uptake is greater in sandy loam than in loamy soil. This phenomenon is usually due to the availability and greater abundance of plant nutrients in loamy soil. The reduction of uptake when lime and organic matter is added is greater for the sandy loam than for loamy soil (33).

As a part of these studies, a critical review of recent literature on the chemical and exchange properties of fallout nuclides in various media was carried out and over 150 references abstracted.

TABLE V

Ion Effects on Nuclide Uptake by Plants

According to Jackson (38)

Salts Added(*)	Water Extractable Cs-137 cpm (x 10-3)/pot of soil	Uptake of Cs-137 cpm (x 10-3)/gm of plant tissue
none	0.70 ± 0.10	24.76 ± 2.50
NH_4Cl	13.72 ± 2.05	44.69 ± 0.98
NH_4NO_3	9.93 ± 1.71	41.40 ± 4.53
$(NH_4)_2SO_4$	11.24 ± 1.71	44.15 ± 1.00
KCl	5.09 ± 1.01	1.23 ± 0.15
KNO_3	4.19 ± 0.52	2.00 ± 0.62
K_2SO_4	4.91 ± 0.63	1.19 ± 0.08
NaCl	1.08 ± 0.30	33.84 ± 3.09
$CaCl_2$	1.64 ± 0.19	34.68 ± 3.73
$MgCl_2$	1.80 ± 0.20	34.94 ± 1.58

(*) The salts were added at 1 meq/100 gm of soil

VI. STATUS OF COMPUTER PROGRAMS

The development of computer programs has followed along the lines suggested in the scope of this research project. An estimation of the number of atoms per unit area, N(A), is a modification of the evaluation of fallout intensity, I(1), at a given location. To this end, a program for interpolation of nuclide solubility contour ratios from data supplied by Miller (61) has been developed. This program is independently useful in that it provides the value of the contour ratio for each downwind distance, or particle size parameter, α. Furthermore, the incorporation of this program into a MAIN program such that the final output will be in atoms per area over a downwind-crosswind surface is nearly completed. A computer flow diagram appears later in this section of the report.

The evaluation of atoms per area for the cumulative effects of a poly-weapon situtation represents an extension of the single weapon atom concentration program. Such a program is necessary for the evaluation of contamination from large-scale attacks affecting watersheds and reservoirs. The program previously developed for multiple weapon evaluation of intensity will represent only a minor portion of the expanded version. A new multiple yield program to compute the total atom concentration at any point or for the entire watershed is now in the developmental stages.

A. Development of Computer Program to Determine Atom Concentration, N(A), Over Any Surface

In the program entitled Soluble Nuclide Contour Ratios, previously presented (1), the computation of N/I (or $N^{o}_{ri}(1)$) was expected ultimately. In the meantime these values have been computed by Miller. Therefore, to facilitate the evaluation of contaminated water supplies, it has been decided to use the nuclide solubility contour ratio data provided by Miller (61). For the evaluation of water contamination due to a surface blast of 5, 10, or 20 MT a tedious procedure had been followed. The difficulty was due to the lack of a completely successful computer program to evaluate the nuclide solubility contour ratios. By incorporating the contour ratios (N/I) computed by Miller into the existing program (62) for intensity evaluation (I), the number of soluble atoms (N) can be found readily. The previously developed program for estimating fallout intensity at any location has been streamlined and modified by incorporating the soluble nuclide contour ratio, $N^{o}_{ri}(1)$, into the MAIN program. Modifications include a subroutine to interpolate for the desired values of $N^{o}_{ri}(1)$, equivalent to N/I, and a multiplication of these contour ratios by the computed intensity values, or

$$N(A) = I(1)N^{o}_{ri}(1) = I \times \frac{N}{I} = N$$

With this modification the final output will be in terms of atoms/area. The outline of the entire program, including this modification, may be seen in the flow diagram, Figure 2.

The table from Miller (61) supplies only values of $N^{o}_{Yi}(1)$ for 1, 10, 100 MT weapons. For this reason it was necessary to interpolate for 5 and 20 MT yields. The V_f (converted to α^*) values in the table are not sufficient for an accurate determination of contamination over large watershed areas. In the flow diagram given below, the SUBROUTINE INTERP is a method of linear interpolation for the necessary α values. The subroutine has been tested separately in a slightly different form and is presented with its flow diagram later in this report as Figures 3 and 4.

The use of a computer program for the direct evaluation of N "(atoms/area) has two justifications:

(1) The large number of coordinate points within a given watershed area may be quite large. Therefore, the number of calculations for intensity and the interpolations for nuclide contour ratio values would be quite voluminous.

(2) By proper selection of coordinates, the computation may be made as accurate as initial assumptions allow. The desired degree of accuracy is achieved by decreasing the square area of evaluation.

In the following pages, the flow diagram for the entire computer program, that for the interpolation subroutine and finally the actual computer program with some output are presented.

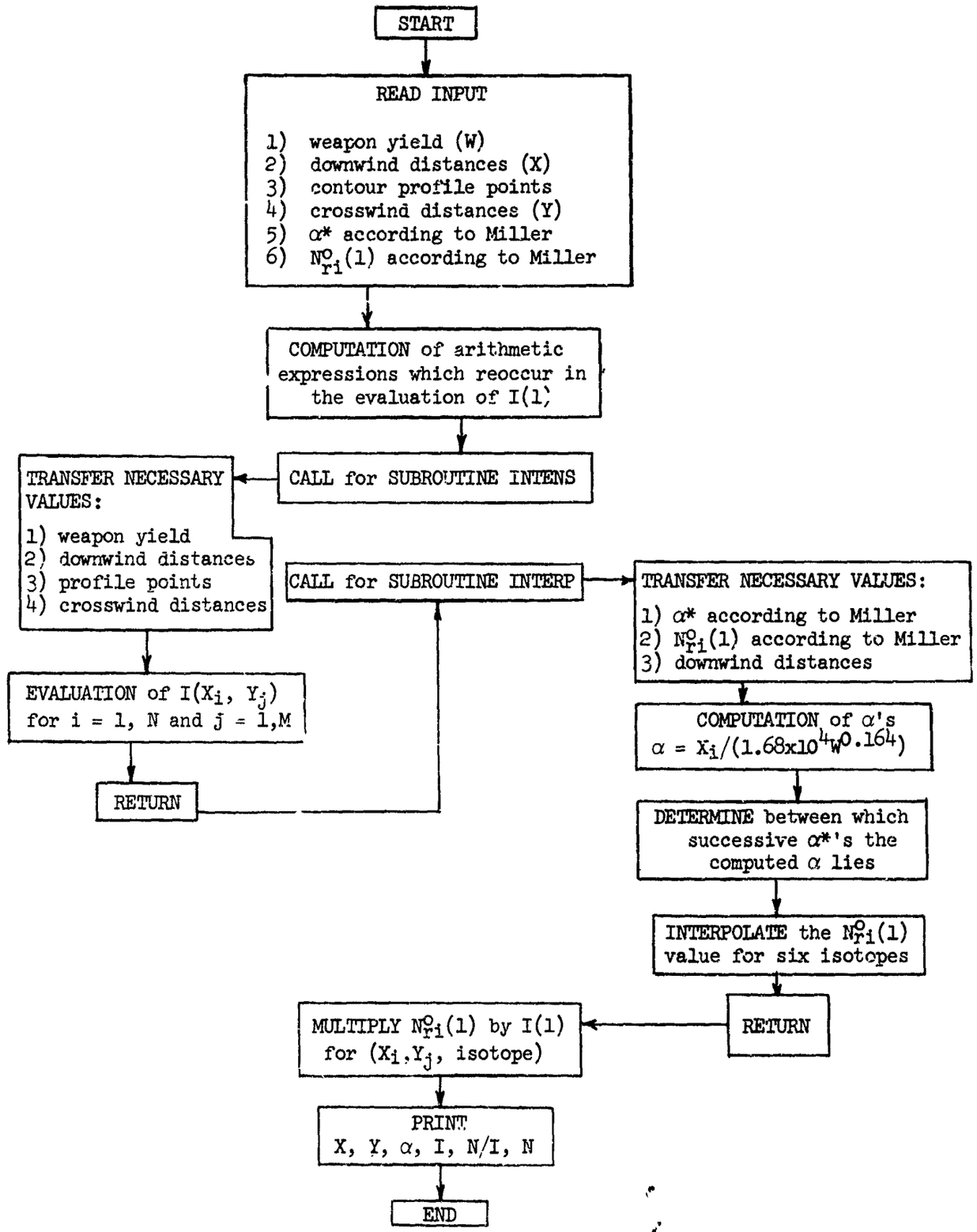


Figure 2. Flow Diagram for Computer Program to Determine Atom Concentration Over Any Surface

Note: α* are values corresponding to V_f selected by Miller (61).
α are values calculated according to the formula, $\alpha=x/h=X_i/(1.68\times10^{4}W^{0.164})$.

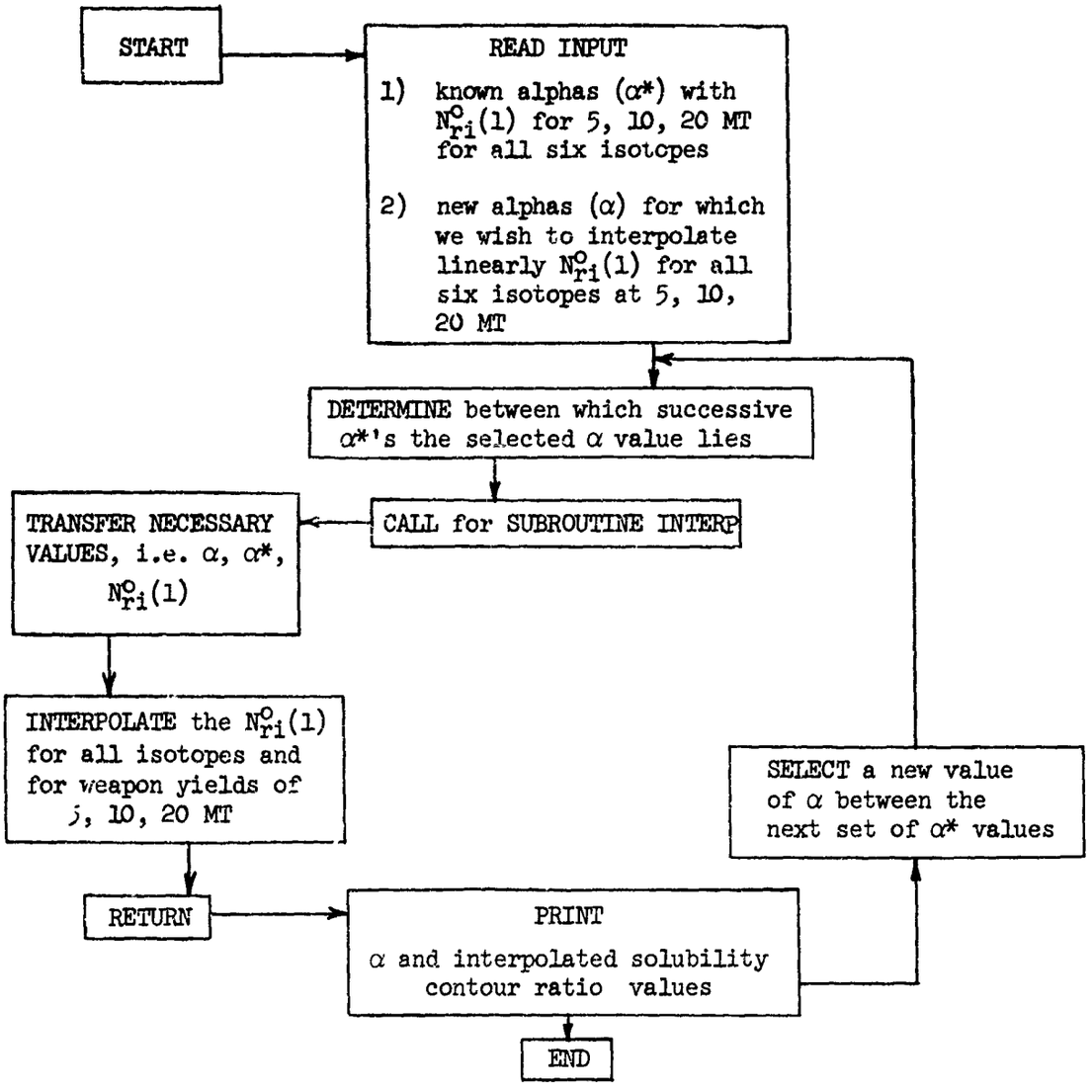


Figure 3. Flow Diagram for the Interpolation of Nuclide Solubility Contour Ratio, $N^{o}_{ri}(1)$, for Values of α between 110 and 0.667(*)

(*) Note: corresponding to values of V_f from 0.2 to 33.0

```
C       INTERPOLATION OF NUCLIDE SOLUBILITY CONTOUR RATIOS
        DIMENSION A(8), ANEW(100), SR89(8,3), SR90(8,3), RU106(8,3),
       1   XI131(8,3), CS137(8,3), BA140(8,3), U(3), V(3), W(3), X(3),
       2  Y(3), Z(3)
        READ 1, N,M,(A(I),I=1,N),(ANEW(K),K=1,M)
        READ 2, ((SR89(I,J),J=1,3),(SR90(I,J),J=1,3),(RU106(I,J),J=1,3),
       1(XI131(I,J),J=1,3), (CS137(I,J),J=1,3),(BA140(I,J),J=1,3),I=1,N)
        DO 11 K=1,M
        DO 10 I=1,N
        IF(ANEW(K)-A(I)) 10,13,12
   10   CONTINUE
   13   PRINT 21, ANEW(K)
   21   FORMAT(22H0ANEW IS A DATA POINT,     F10.5)
        GO TO 11
   12   CALL INTER(I,K,A,ANEW,SR89,SR90,RU106,XI131,CS137,BA140,
       1U,V,W,X,Y,Z)
        PRINT 20, ANEW(K), U, V, W, X, Y, Z
   11   CONTINUE
   20   FORMAT(40H1THE ALPHA WE ARE INTERPOLATING ABOUT IS,      F10.5//
       125H0THE VALUES FOR SR89 ARE,     3F10.3//25H0THE VALUES FOR SR90 AR
       2E,     3F10.3//26H0THE VALUES FOR RU106 ARE,    3F10.3// 26H0THE VAL
       3UES FOR XI131 ARE,     3F10.3//26H0THE VALUES FOR CS137 ARE,  3F10
       4.3//26H0THE VALUES FOR BA140 ARE,    3F10.3//////)
    1   FORMAT(2I5/(8F10.4))
    2   FORMAT(6F12.4)
        CALL EXIT
        END


        SUBROUTINE INTER(I,K,A,ANEW,SR89,SR90,RU106,XI131,CS137,BA140,U,
       1V,W,X,Y,Z)
        DIMENSION A(8), ANEW(100), SR89(8,3), SR90(8,3), RU106(8,3),
       *   XI131(8,3), CS137(8,3), BA140(8,3), U(3), V(3), W(3), X(3),
       2  Y(3), Z(3)
        B=(ANEW(K)-A(I))
        C=(A(I-1)-A(I))
        DO 10 J=1,3
   10   U(J)=(SR89(I-1,J)-SR89(I,J))*B/C+SR89(I,J)
        DO 11 J=1,3
   11   V(J)=(SR90(I-1,J)-SR90(I,J))*B/C+SR90(I,J)
        DO 12 J=1,3
   12   W(J)=(RU106(I-1,J)-RU106(I,J))*B/C+RU106(I,J)
        DO 13 J=1,3
   13   X(J)=(XI131(I-1,J)-XI131(I,J))*B/C+XI131(I,J)
        DO 14 J=1,3
   14   Y(J)=(CS137(I-1,J)-CS137(I,J))*B/C+CS137(I,J)
        DO 15 J=1,3
   15   Z(J)=(BA140(I-1,J)-BA140(I,J))*B/C+BA140(I,J)
        RETURN
        END
*       DATA
```

Figure 4. Computer Program for Interpolation of Nuclide Solubility Contour Ratio, $N^{o}_{ri}(1)$, for Values of α between 110 and 0.667 (*)

(*) Note: corresponding to values of V_f from 0.2 to 33.0

PART OF THE RESULTS

THE ALPHA WE ARE INTERPOLATING ABOUT IS 0.74100

	5MT	10MT	20MT
THE VALUES FOR SR89 ARE	0.470	0.023	0.020
THE VALUES FOR SR90 ARE	0.380	0.197	0.145
THE VALUES FOR RU106 ARE	0.125	0.095	0.045
THE VALUES FOR XI131 ARE	0.085	0.055	0.006
THE VALUES FOR CS137 ARE	0.100	0.075	0.040
THE VALUES FOR BA140 ARE	1.165	0.564	0.503

THE ALPHA WE ARE INTERPOLATING ABOUT IS 68.75

	5MT	10MT	20MT
THE VALUES FOR SR89 ARE	4.180	4.360	4.581
THE VALUES FOR SR90 ARE	0.000	5.245	5.099
THE VALUES FOR RU106 ARE	2.220	2.360	2.357
THE VALUES FOR XI131 ARE	0.923	1.015	1.054
THE VALUES FOR CS137 ARE	6.665	7.850	7.904
THE VALUES FOR BA140 ARE	6.495	5.705	5.370

Figure 4. (cont'd) Computer Program for Interpolation of Nuclide Solubility Contour Ratio, $N^{o}_{ri}(1)$, for Values of α between 110 and 0.667 (*)

(*) Note: corresponding to values of V_f from 0.2 to 33.0

3. Development of Multiple Weapon Program

Incorporation of contour ratio data into the intensity evaluation program implies a similar extension of the multiple weapon intensity program. The multiple weapon program presented in the previous report (1), was inefficient and required considerable streamlining. The new multiple weapon program necessarily follows a successful single weapon yield program. Though not completed, the program is expected to follow the guidelines of the following flow diagram.

It should be noted that $N^{o}_{ri}(1)$ values are interpolated in a subroutine from the data supplied by Miller (61). Also, there are two subprograms available for the translation of axes. One of these uses the rotation of axes presented in the previous report (1). The other subroutine assumes parallel axes. In some instances a method of parallel translation may be more appropriate. Since jet streams and upper air wind patterns do not change radically, two target cities may well experience the same wind direction. In fact, if two differing ground zero blasts are to have a noticeable effect on a watershed area, they will certainly be within a six hundred mile range of each other. It can be expected that in such a case the wind directions at both sites would be approximately equal. In this case the parallel translation of axes would be the more appropriate method of analysis.

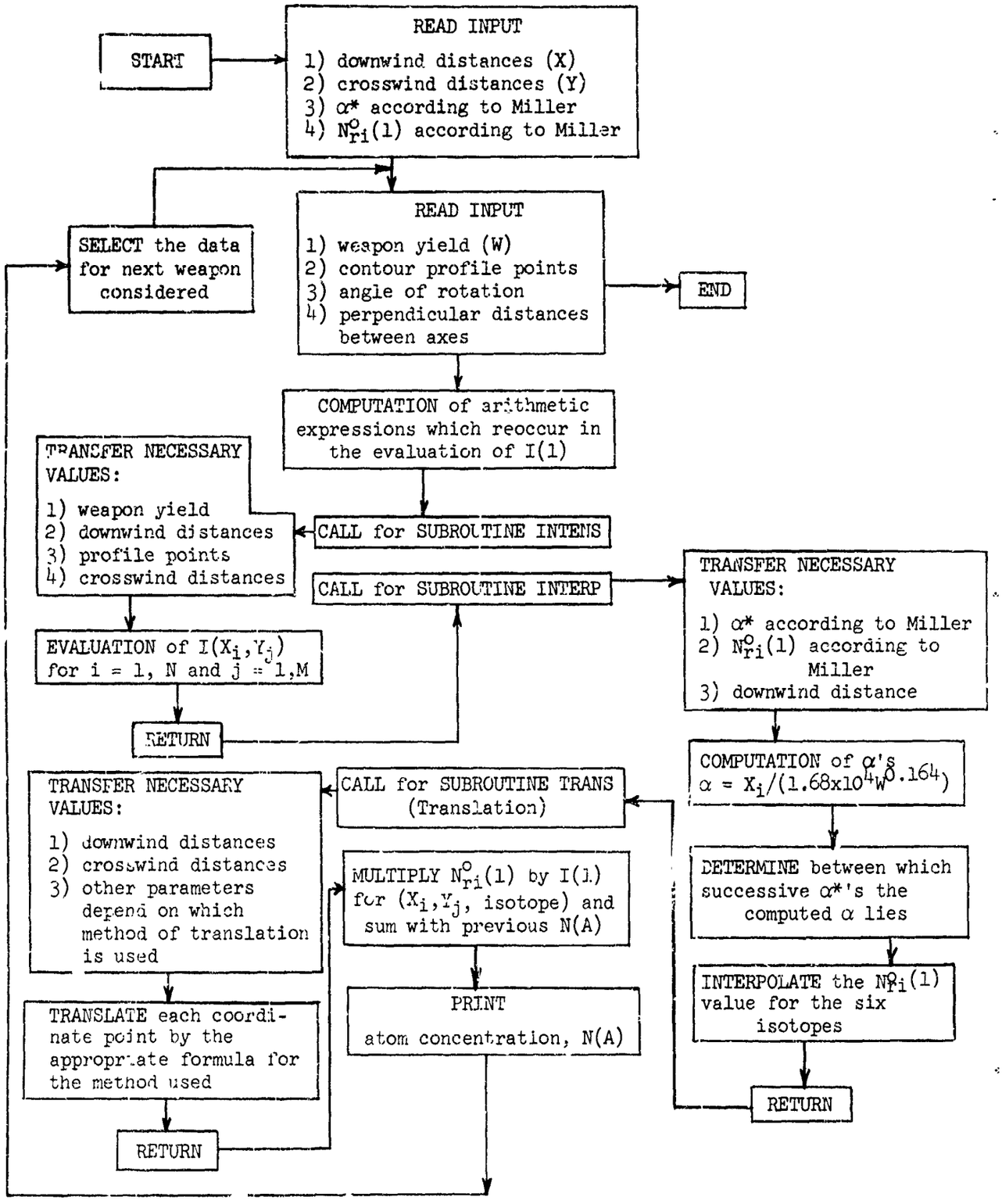


Figure 5. Flow Diagram for Atom Concentration at Any Location for Multiple Weapons Computer Program

VIII. PRELIMINARY EVALUATION OF CONTAMINATION OF THE PROVIDENCE, R.I., WATER SUPPLY

A. Selection of Attack and Orientation of Fallout Model

A preliminary evaluation of fallout contamination in the Providence, Rhode Island, water supply system was carried out during the initial phase of this research program in preparation for the Five-City Study, sponsored by the Office of Civil Defense.

In consideration of the limitations in time and resources for this phase of the study and in the absence of an operational multiple weapon program, it was decided to follow the previously reported Technical Operations, Inc. attack model (63) to provide the fallout contamination over the Providence, R.I. watershed, with an assigned wind velocity of 15 mph. Ultimately the study will examine a variety of attack conditions. It followed logically to select Springfield, Massachusetts, as the target city because of the predominant wind direction and to supply an additional 10 MT weapon to approximate the effect of the other weapons in the attack model. Location of the weapons with ground zero at Springfield, Massachusetts, probably accounts for over 80% of the fallout on the Providence, R.I., watershed. Therefore, the fallout pattern downwind axis was oriented in an east-southeast direction, as illustrated in Figure 6, for the following reasons:

1) The predominant wind direction at Providence, R.I., is west-northwest. Since the fallout level at any particular point downwind is very sensitive to wind direction and the entire watershed is located due west of the city, location of ground zero at Providence would not provide fallout contamination of the city's system of water supply reservoirs.

2) The relevant geographic industrial and military target areas presented in the attack model (63) and consideration of their locations relative to the Providence watershed led to the selection of one 10 MT and 20 MT weapon detonated at Springfield, Massachusetts, situated 60 miles west-northwest or Providence, Rhode Island.

It should be pointed out that these estimates of water contamination, for six biologically important radionuclides, as well as those reported for other target cities previously (1), consider the effect from an attack on a single target area only. In any general, multiple-weapon attack on the continental United States, fallout from weapons detonated over other target areas would result in overlapping of coverage and increase the contamination level over reservoirs and in water supplies. An unclassified attack pattern for use in the initial analysis of the Five-City Study has been evolved, but this Guide (64) was not received until after the work covered in this report had been completed.

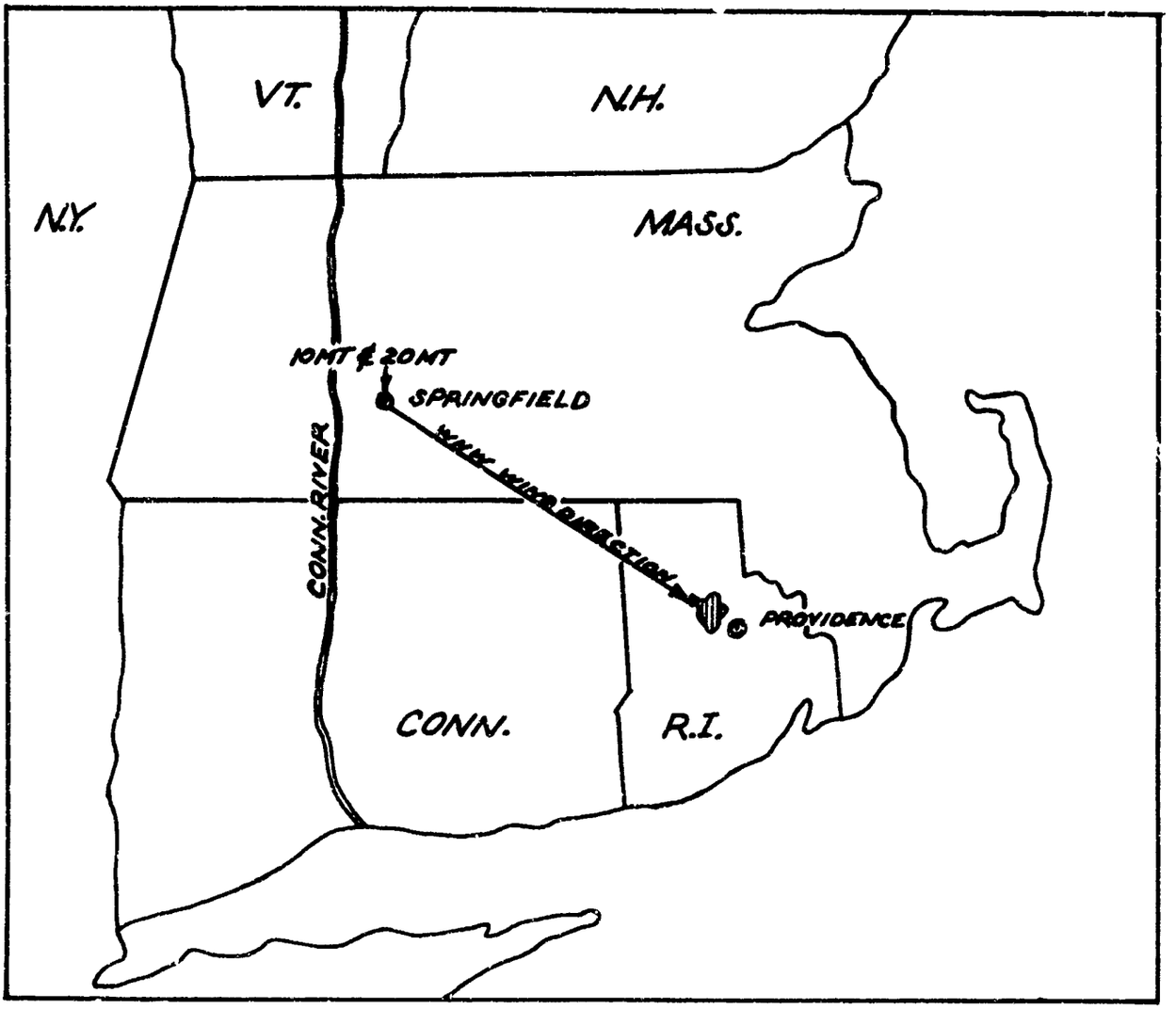


Figure 6. Location of Ground Zero for Evaluation of Providence Water Supply Contamination

B. Providence Water Supply System

The present system of water supply for the City of Providence was constructed under the supervision of a commission of seven members, known as the Water Supply Board, created in accordance with Chapter 1278 of the Public Laws of Rhode Island and approved on April 21, 1915. The Cities of Providence and Cranston along with the Towns of Johnston and North Providence are supplied through a distribution system owned and maintained by Providence. Parts of the City of Warwick and portions of the Towns of West Warwick and Coventry served by the Kent County Water Authority, along with the East Smithfield Water District, are furnished water on a wholesale basis but own the distribution system within their respective communities. Other towns entitled to Providence Water under legislative acts, but not being supplied at present, are Scituate, Foster, and Glocester. These cities and towns represent about 377 sq. mi., or about 36% of the land area of the State of Rhode Island.

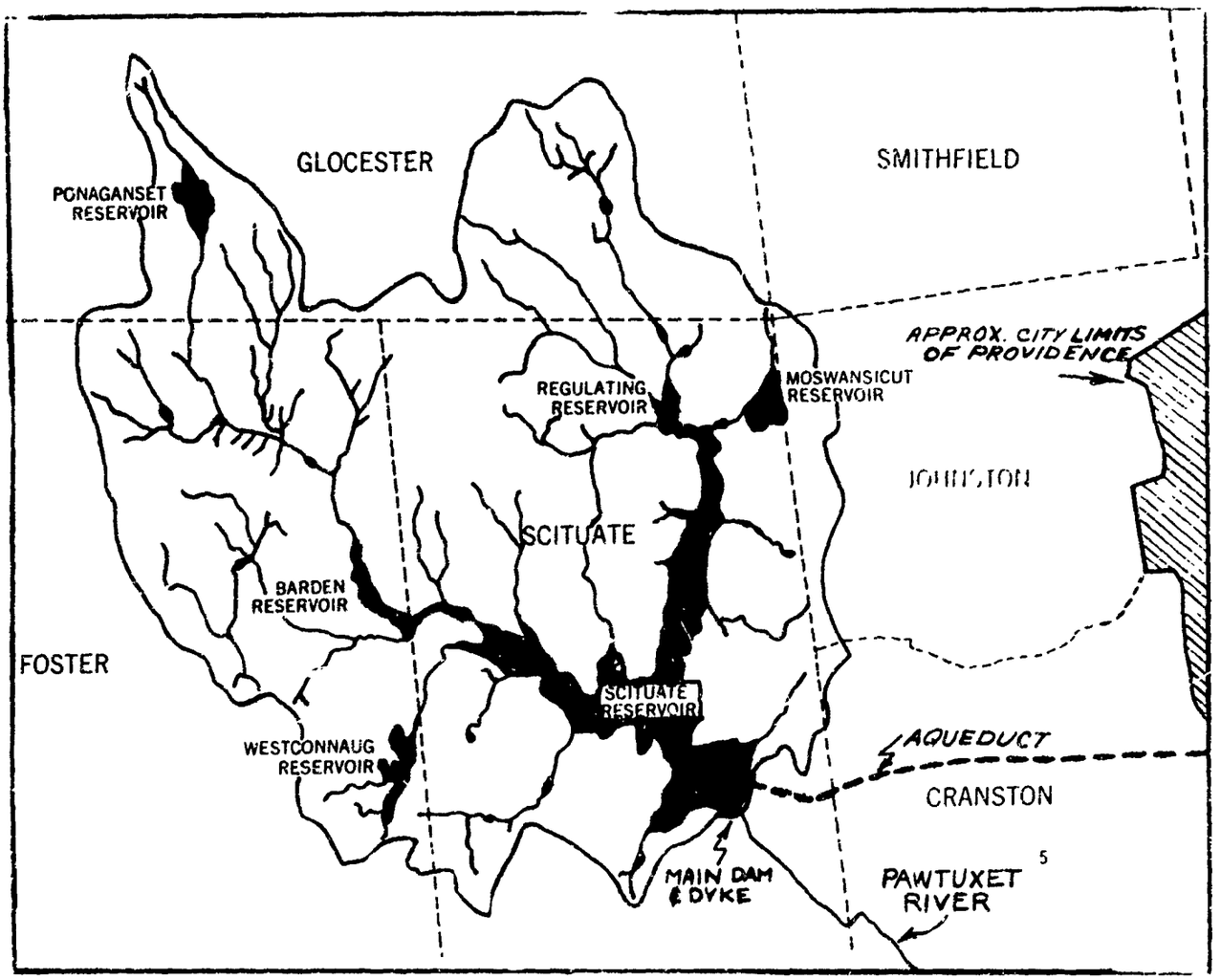
1. Water Consumption

Based on the 1960 census, the Providence Water Supply Board provides water to 45% of the population of the state of Rhode Island. In 1962, the eight cities and towns receiving Providence Water used 45.72 million gallons per day. Coincidental with the severe drought, the average daily water consumption increased to an all-time record for the water year ending September 30, 1965. During this period, the cities and towns supplied from the Providence system consumed 54.6 million gallons per day(*). According to the 1965 Annual Report of the Providence Water Supply Board (65) a total population of approximately 383,635 is served by the system. The rate of daily water consumption has increased from approximately 119 gallons per capita in 1962 to 139 gallons per capita in 1965, or almost 17%, which may be at least partially attributable to the prolonged drought experienced in the Northeast.

2. Watershed

Providence obtains its water from a surface supply located on the north branch of the Pawtuxet River. The total watershed area covers 92.8 sq.mi., as shown in Figure 7. The watershed area is about five times the area of the City of Providence. This drainage basin represents approximately 9% of the land area of the State of Rhode Island. The City owns 23.93 sq. mi., or slightly over 25% of the land in the drainage area, or about 5 sq. mi. more than the 18.91 sq. mi. area of the City of Providence (66).

(*)The total annual draft from the Scituate Watershed for 1965 was 25.06 billion gallons, or an average of 68.65 million gallons per day. The average daily draft for water supply purposes was 54.6 million gallons and the difference of 14.05 million gallons per day was discharged into the north branch of the Pawtuxet River.



NOTE: Distance from main dam to center of Providence = 10 mi.

Figure 7. WATERSHED OF PROVIDENCE, R.I. WATER SUPPLY

3. Reservoir System

All surface water from the watershed is ultimately collected in the main reservoir, known as the Scituate Reservoir. Five smaller reservoirs: Moswansicut, Regulating, Ponaganset, Barden and Westconnaug are tributary to the main reservoir. Further information on these reservoirs is presented in Table VI below.

TABLE VI

Providence, Rhode Island, Water Supply Reservoirs

Reservoir (Name)	Watershed Area (sq. mi.)	Storage Capacity (million gallons)	Water Surface (sq. mi.)	Spillway Elevation (feet)
Scituate	92.8	37,011	5.30	284.01
Moswansicut	3.9	1,781	0.44	301.90
Regulating	22.3	428	0.38	285.50
Ponaganset	2.1	724	0.36	633.05
Barden	33.0	853	0.38	345.10
Westconnaug	4.0	453	0.27	454.17

All five small reservoirs were originally owned and controlled by mills located along the Pawtuxet River and were acquired by the City under the provisions of the 1915 Water Act. Gross storage in all reservoirs totals 41.268 billion gallons but the dead storage amounts to 1.522 billion gallons, which leaves a total available storage of 39.746 billion gallons.

At the end of the water year, September 30, 1965, the combined storage was 29.407 billion gallons, or 71.3% of capacity. The maximum combined storage occurred on May 2, 1965, when 38.55 billion gallons, or 93.4% of capacity, were impounded. The total annual draft from the Scituate Watershed was 25.056 billion gallons, or an average of 68.65 million gallons per day. The total annual draft for water supply purposes was 19.93 billion gallons, or an average of 54.6 million gallons per day.

4. Hydrology

The average annual rainfall on the watershed is 48.42 inches, based on the 47-year average (1915-1962), with a 66.28 in. yearly maximum (1953) and a 33.43 in. yearly minimum (1957). The average yearly runoff, or water actually collected in the reservoirs, based on the same period of record, is 25.12 inches. Every inch of runoff over the 92.8 sq. mi. watershed is equivalent to a volume of 1,612,750,000 gallons. Multiplying this figure by the long-term average runoff of 25.12 in. and dividing by 365 days shows an average yield of 110,990,000 gallong daily, or about twice the average quantity of raw water delivered daily to the Water Purification Works. However, the estimated safe yield of the Scituate Supply is 84,020,000 gallons per day.

Rainfall on the 92.8 sq. mi. Scituate Watershed, due to the extended severe drought, was only 38.13 in. for the year ended September 30, 1965. This was the fourth lowest annual rainfall experienced during the 50-year (1916-1965) period of record; it was 9.91 in. less than the long-term average of 48.04 inches.

The runoff for the year 1965 totalled 14.26 in. which was 10.40 in. less than the 50-year (1916-1965) average of 24.66 inches. It was the third lowest annual runoff during the 50 years of record.

For the year 1965, the yield from the Scituate Watershed was 22.99 billion gallons, or an average of 62.99 million gallons per day, which was 5.65 million gallons per day less than the average daily draft, and 45.897 million gallons per day less than the 108.89 million gallons per day average yield for the 50-year period 1916 through 1965.

5. Watershed Management

The City of Providence has a highly developed system of watershed maintenance and management. All forestry operations on the watershed are under the management of a professional forester who supervises the work on over 11,000 acres of City-owned forest land that surrounds the main Scituate Reservoir and the five smaller reservoirs. Practically all the arable areas have been planted with conifers such as White Pine, Red Pine, Scotch Pine, Austrian Pine, Jack Pine, White Spruce, Norway Spruce, etc. Much of the wooded area, particularly that upon which low-quality oak and hardwood grew, has been underplanted with coniferous species. Approximately 7,000,000 trees have been planted on watershed lands owned by the City.

Forest cover is essential on the Scituate Reservoir watersned for the storage and supply of high quality water. A thick leaf litter on the forest floor serves as a soft, spongy surface to absorb the rain and melting snow. The undisturbed porous soil underneath the litter layer acts as a large storage area. Some of the water in this soil-storage area is available for use and transpiration by trees and other plant life. The excess water filters gradually through the soil and ultimately empties into streams which flow into the reservoir system.

As the plantations reach 25 to 30 years of age, thinning or improvement cutting to maintain a thrifty stand of trees is practiced. However, before all mature trees are removed from a forest stand, an adequate supply of natural reproduction has become established. Reinforcement plantings of seedlings obtained from a forest nursery are also used. Timber operations remove from the watershed such important wood products as pulpwood, firewood, poles for piling, and sawlogs.

A continuous development of the watershed management program is proceeding in a number of areas such as: (1) work toward a master plan for the sustained management of the watershed forests; (2) effective control of timber-harvest and timber-culture operations; (3) inspection and protection of property boundaries and watershed forests; (4) research and study of vegetative influences on the watershed; and (5) supplemental support of administrative and supervisory functions.

The role of forest cover in providing an adequate supply of high quality water is a major consideration of the Water Supply Board. Therefore, modern and efficient techniques are continually being applied in forestry and maintenance operation on the watershed.

6. Intake and Treatment Works

Water is conveyed from Scituate Reservoir by gravity and through aqueducts to the Water Treatment Works, where ferric sulphate is added as a coagulant. The chemical treated water is then subjected to an influent aerator to remove carbon dioxide which has corrosive properties and other gases which may produce disagreeable taste and odors. Influent aeration is also practiced to oxidize iron and manganese to be removed in the coagulation and sedimentation processes which follow.

From the influent aerators, the water continues under gravity to a large, circular mixer. The tangentially entering stream can be regulated to produce desired velocities to insure thorough mixing of the chemicals. Slaked quicklime is introduced to the water just ahead of the mixer. The lime aids in reducing the corrosive properties of the water by raising the pH of the water from an acid to an alkaline state. This treatment is necessary for the removal of iron and manganese which cannot be removed at a low pH, and affords a better degree of coagulation by increasing the specific gravity of the ferric hydroxide floc.

After a detention period of two to three days in the coagulation and sedimentation basins, which have a combined capacity of 160.21 MG, the water is drawn through rapid sand filters, chlorinated and treated with sodium silico-fluoride, and then discharged into a clear well for distribution through the 4.5 mile aqueduct to the city.

In case of breakdown or repairs to the purification works or the main aqueduct, there is reserve storage in three underground concrete reservoirs within the system. Neutaconkanut Reservoir in Johnston stores about 38.58 MG at its normal operating level; while Aqueduct Reservoir in Cranston holds 40.03 MG at normal operating level. The third reserve storage reservoir, Longview, located in North Providence, contains 11.94 MG at normal elevation. The combined storage capacity of all three reservoirs is sufficient storage for two days' supply based on the average daily consumption and represents one day reserve at the rate of the maximum day.

C. Method of Evaluation for Water Contamination

1. Basic Assumptions

The basic assumptions and method of evaluation are essentially those presented previously (1)(67). Radionuclides from fallout are assumed to mix homogeneously in a water supply reservoir following deposition on the water surface. Therefore, the concentration of a radionuclide in water may be determined from a knowledge of the nuclide surface density, the reservoir surface area and volume of the body of water.

A second assumption is that the parent elements of all long-lived radionuclides of interest have already decayed to a negligible amount at H + 1 hour. The nuclide concentration estimates are calculated from

fallout intensity contours corrected to H + 1 hour. This correction means that after local fallout stops, essentially 24 hours after detonation, the existing fallout patterns are traced back to a common time basis at one hour after weapon detonation by use of a typical ionization rate decay curve. The following relationship may then be used to obtain activity concentration from nuclide concentrations in water:

$$A = \lambda N_c \qquad (11)$$

where: A = the activity concentration in water (curies per unit volume)

λ = the radioactive decay constant ($time^{-1}$)

N_c = nuclide concentration in water (atoms per unit volume)

2. General Procedure

The contamination in water supplies may be derived from any one of four sources or any combination of these:

a. Reservoir Supplies:

(1) Direct contamination

(2) Contamination from feeder streams

(3) Contamination from watershed runoff

(4) Contaminated ground water inflow

b. Stream Supplies:

(1) Direct contamination

(2) Contamination from runoff

(3) Contaminated groundwater inflow

The evaluation is performed in two stages. First, the effect from a single weapon is analyzed, then by the principle of superposition, the combined effect of several weapons is determined.

The general procedure may be outlined as follows:

a. The fallout pattern for each assumed weaponage is superimposed over the area map with ground zero coinciding with the target point, and the downwind axis parallel to the prevailing wind direction.

b. Working from the fallout model, the soluble nuclide surface density is evaluated and integrated over the surface area of interest and the result divided by the total volume of water to obtain the nuclide concentration in water. The activity concentration, A, is then estimated from Equation (11).

3. Runoff

Contamination due to runoff is based on the assumption that all the nuclides which are distributed over the watershed enter the water supply system in one form or another. As part of this research program investigations are currently underway to determine to what extent this assumption is valid or if the number of nuclides deposited on a surface and entering a water supply system is significantly reduced from 100 per cent due to factors such as vegetative and soil uptake.

Runoff volume is calculated from the relationship $Q = C\ i\ A$; where C is an average runoff coefficient determined from rainfall and runoff records; i is the estimated maximum rainfall intensity; and A is the watershed surface area.

The combined effect of direct surface and runoff contamination is obtained by computing a weighted average of the radioactive concentrations calculated for each case.

D. Absorbed Dose

During a nuclear attack, public water supply systems are subject to severe damages and the contents exposed to fallout contamination. Soluble radionuclides mix with the feeder streams of a watershed and tend to increase the radioactivity in the water. When this water is consumed it may constitute a major source of the internal radiation hazard.

A number of mathematical models for estimating the absorbed dose from assimilation of radionuclides in body organs of humans have been developed. Estimates reported here are based on the Miller-Brown Model of Biological Uptake and were determined according to criteria presented in a previous report entitled, "Evaluation of Fallout Contamination of Water Supplies" (1).

E. Results

The concentrations of six biologically important radionuclides in the Providence water supply system at H + 1 hour following a 30 MT nuclear attack at Springfield are presented in Table VII.

Assuming a standard intake of one liter per person per day, the absorbed dose for total body organs for different starting times after detonation t_o, and ingestion periods t, has been summarized in Table VIII.

F. Discussion of Results

A summary of the water contamination levels and decontamination requirements for the six biologically important radiosotopes investigated is presented in Table IX. As may be seen, the activity levels from surface contamination of I-131 and Ba-140 exceed 10^{-3} $\mu c/m\ell$, the tentative emergency standard according to Bale (68). Peacetime continuous occupational exposure MPC (69) values for I-131 and Ba-140 in drinking water are 6×10^{-5} $\mu c/m\ell$ and 8×10^{-4} $\mu c/m\ell$, respectively.

Although the contamination levels calculated for the Providence, R.I. water supply are higher than those calculated for other municipal water supplies (1) the results agree reasonably well. It can be expected that a more refined analysis of contamination to the Providence water supply (including the effects of stream flow between reservoirs, sedimentation, and the factors affecting runoff) will reduce the given estimates to a range within those previously calculated for other municipalities, especially since ion exchange and plant uptake phenomena are expected to decrease the level of water contamination.

TABLE VII

Contamination of Providence, Rhode Island, Water Supply

System	Isotope	atom/liter($\times 10^{12}$)	μc/ml
Westconnaug Reservoir	Sr-89	3.36	1.37×10^{-2}
	Sr-90	5.91	1.26×10^{-4}
	Ru-106	2.80	1.66×10^{-3}
	I-131	6.15	1.66×10^{-1}
	Cs-137	4.28	7.63×10^{-5}
	Ba-140	6.21	1.05×10^{-1}
Ponaganset Reservoir	Sr-89	1.69	6.87×10^{-3}
	Sr-90	3.38	7.19×10^{-5}
	Ru-106	1.62	9.63×10^{-4}
	I-131	3.55	9.57×10^{-2}
	Cs-137	2.35	4.19×10^{-5}
	Ba-140	3.57	6.03×10^{-2}
Barden Reservoir	Sr-89	2.32	9.43×10^{-3}
	Sr-90	4.49	9.55×10^{-5}
	Ru-106	2.12	1.26×10^{-3}
	I-131	4.66	1.26×10^{-1}
	Cs-137	3.22	5.74×10^{-5}
	Ba-140	4.72	7.97×10^{-2}
Moswansicut Reservoir	Sr-89	0.546	2.22×10^{-3}
	Sr-90	1.04	2.21×10^{-5}
	Ru-106	0.488	2.90×10^{-4}
	I-131	1.07	2.88×10^{-2}
	Cs-137	0.767	1.37×10^{-5}
	Ba-140	1.09	1.84×10^{-2}

TABLE VII (Cont'd)

Contamination of Providence, Rhode Island, Water Supply

System	Isotope	atom/liter($\times 10^{-12}$)	uc/ml
Regulating Reservoir	Sr-89	2.33	9.47×10^{-3}
	Sr-90	4.46	9.48×10^{-5}
	Ru-106	2.11	1.25×10^{-3}
	I-131	4.63	1.25×10^{-1}
	Cs-137	3.27	5.83×10^{-5}
	Ba-140	4.70	7.94×10^{-2}
Scituate Reservoir	Sr-89	0.683	2.78×10^{-3}
	Sr-90	1.29	2.74×10^{-5}
	Ru-106	0.614	3.64×10^{-4}
	I-131	1.35	3.64×10^{-2}
	Cs-137	0.959	1.71×10^{-5}
	Ba-140	1.36	2.30×10^{-2}
Entire System	Sr-89	1.21	4.91×10^{-3}
	Sr-90	1.47	3.13×10^{-5}
	Ru-106	0.698	4.15×10^{-4}
	I-131	1.53	4.12×10^{-2}
	Cs-137	1.08	1.92×10^{-5}
	Ba-140	1.54	2.60×10^{-2}
Entire System Including Runoff	Sr-89	18.1	7.34×10^{-2}
	Sr-90	34.9	7.42×10^{-4}
	Ru-106	16.6	9.86×10^{-3}
	I-131	36.4	9.81×10^{-1}
	Cs-137	25.2	4.49×10^{-4}
	Ba-140	36.6	6.18×10^{-1}

TABLE VIII

Internal Hazard of Total Body from Ingestion of Contaminated Providence Water Supply (rems)

Isotope	t_c (days)	t_o (days)	Dose due to direct contamination of reservoir	Dose due to the effect of runoff included
Sr-89	1	30	0.188	2.80
		91	1.11	16.6
	7	30	0.115	1.72
		91	0.939	14.0
	14	30	0.0536	0.80
		91	0.761	11.3
Sr-90	1	30	0.00316	0.0750
		91	0.030	0.712
	7	30	0.00198	0.0471
		91	0.0260	0.618
	14	30	0.000986	0.0234
		91	0.0219	0.520
Ru-106	1	30	0.00244	0.0581
		91	0.00956	0.227
	7	30	0.00173	0.412
		91	0.00879	0.209
	14	30	0.000977	0.0232
		91	0.00789	0.188
I-131	1	30	1.10	26.2
		91	1.51	35.9
	7	30	0.545	13.0
		91	0.898	21.4
	14	30	0.203	4.84
		91	0.490	11.6
Cs-137	1	30	0.00313	0.0731
		91	0.0252	0.587
	7	30	0.00201	0.0469
		91	0.0222	0.519
	14	30	0.000989	0.0231
		91	0.0191	0.446
Ba-140	1	30	0.0524	1.24
		91	0.0996	2.37
	7	30	0.0291	0.692
		91	0.0713	1.69
	14	30	0.0124	0.294
		91	0.0480	1.14

TABLE IX

Summary of Water Contamination Levels for the Providence, R.I., Water Supply

(all values given are in $\mu c/m\ell$)

Isotope	Surface Contamination	Contamination, including runoff
Sr-89	4.91×10^{-3}	7.34×10^{-2}
Sr-90	3.13×10^{-5}	7.42×10^{-4}
Ru-106	4.15×10^{-4}	9.86×10^{-3}
I-131	4.12×10^{-2}	9.81×10^{-1}
Cs-137	1.92×10^{-5}	4.49×10^{-4}
Ba-140	2.60×10^{-2}	6.18×10^{-1}

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13 ABSTRACT Previous studies of water supply contamination from fallout due to nuclear attack indicated that the level of activity brought into a water supply by surface runoff increases the activity considerably. These studies employed a constant value for the "runoff-coefficient" to obtain estimates of the degree of contamination resulting from the soluble fraction of fallout. This report summarizes known relationships between rainfall and the amount of activity that reaches the water supply due to surface runoff and is concerned mainly with the hydrology of surface runoff and ion exchange phenomena. Data on ion exchange properties of soils with respect to the biologically important radionuclides are given. Further, the report includes a consideration of the general problem of transport of activity, a discussion of uptake of activity by biota and preliminary calculations of water supply contamination for Providence, R.I., one of the cities in the OCD "5-City Study". Maximum levels of selected contaminants at the Providence water intake from a 30 MT attack indicate that the water supply contamination level may be increased by a factor of 10 to 25 when surface runoff from the watershed is considered.

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