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HYDROLOGY RESEARCH NEEDS FOR UPSTREAM FLOOD PREVENTION*

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ABSTRACT

The watershed has long been recognized in conservation acts of the Federal Congress of the United States of America as the most effective unit for planning land and water resources development and protection. The Watershed Protection and Flood Prevention Act, Public Law No. 566, enacted in 1954, is the latest Federal legislation relating to upstream watershed programs.

Eight thousand three hundred small watersheds, up to 400 square miles in size, comprising half the land area of the U.S.A., need flood protection and related land and water resources development. Their protection and development may be authorised for joint projects of local, state, and Federal agencies under Public Law-566. Planning and design of such upstream watershed protection and development projects is the responsibility of the U. S. Department of Agriculture. The Department's Agricultural Research Service conducts research in specific support of this program.

Protection from flood and associated sediment damage is the dominant problem. However, many of these watersheds need *multipurpose* projects for their best protection and utilization. Additional needs involve domestic and irrigation water supplies, drainage, recreation, fish and wildlife protection, and low-flow

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regulation for pollution abatement. An estimated 4,000 of these watersheds need drainage improvement, and 2,600 need irrigation facilities.

Planning and design have been accomplished for approximately 8% of the upstream watersheds needing PL-566 projects. Those remaining will involve increasingly complex problems. Prediction of flood flows and effects of watershed modifications on streamflow regimes is basic to economical and effective project plans, and safe and efficient design of structures.

Limitations of existing research information for such prediction are recognized. Much of the information on which hydrologic designs must now be developed has come from small-plot and small-watershed experiments designed for other purposes. Additional information is needed for better understanding of storm runoff generative processes. Data is needed from numerous types of unit-source watersheds representing various combinations of soil-plant and geologic influences, as these interact to determine the flood runoff characteristics of hydrologically significant watershed sub-areas.

A major need is for better information on time-depth-area characteristics of convectional rainstorms, as these vary with geographic region and local orographic influences. Limited research information now being obtained in scattered areas of the United States indicates the limitations of present rainfall information for adequate flood runoff prediction.

Streamflow hydraulics research is needed for development of more feasible and precise methods of routing the flood runoff from headwaters areas, through complex channel systems, for synthesis of downstream flood hydrographs. Limited research on this aspect of the hydrology of flood runoff prediction is currently underway.

Important needs exist for basic hydrologic information for planning and design of upstream flood prevention and related irrigation, drainage, and other improvement on small watersheds in the United States. These needs are engaging the concerted efforts of hydrologists, meteorologists, hydraulicians, geologists, and plant and soil scientists in comprehensive watershed research. Much more such research is needed.

RESUME

Le bassin (*watershed*) a été, depuis longtemps, considéré, dans les lois votées par le Congrès Fédéral des Etats-Unis d'Amérique au sujet de la conservation, comme l'unité la plus efficace par laquelle projeter la développement et la protection des ressources naturelles d'eaux et de terres. La Loi Publique numéro 566, votée en 1954 pour la Sauvegarde des Bassins et pour les Mesures Préventives contre les Inondations est le projet législatif le plus récent qui traite les programmes des bassins d'amont.

La protection contre les inondations, et le développement des ressources naturelles qui s'y rapportent sont devenus nécessaries à huit mil trois cents petits bassins, c'est-à'dire à presque 400 miles carrés qui, ensemble, comprennent la moitié du terrain total des Etats-Unis. Grâce à la Loi Publique numéro 566, il est possible aux agences locales, fédérales et à celles des états de participer conjointement au développement et à la sauvegarde des bassins. C'est la responsabilité du Départment de l'Agriculture des Etats-Unis de concevoir et d'organiser ces projets. Le Service de Recherche Agricole du Départment de l'Agriculture fait des études se rapportant spécifiquement à ce programme.

La protection contre les inondations et les dommages correspondants du sédiment sont problèmes prédominants. Cependant, beaucoup de ces bassins nécessitent de projets *à buts multiples* afin d'assurer leur protection et leur utilisation au plus haut degré. De plus, il y a besoin de ressources d'eaux pour l'usage domestique et pour l'irrigation; de sauvegarde pour la faune, les poissons, et les conditions récréatives; de systèmes de drainage; et de régulation du flux pour diminuer la pollution. On a calculé qu'à peu près 4,000 de ces bassins ont besoin de meilleurs systèmes de drainage, et que 2,600 en demandent des facilitiés d'irrigation.

Les plans préliminaires ont été accomplis pour approximativement huit pour cent des bassins d'amont ayant besoin de profiter des projets rendus possibles par la Loi Publique numéro 566. Celles qui restent entraîneront des problèmes progressivement complexes. Savoir prédire le cours des inondations, et l'influence des modifications des bassins sur les regimes des courants est fondamental au développement efficace et économique des projets, aussi bien qu'à la construction sûre des structures.

Il est évident que les renseignments actuellement accessibles sur de telles prédictions sont insuffisants. Ce sont les expériences sur les petits bassins et sur les petites parcelles de terrain, expériences disposées originellment à d'autres buts, qui nous ont fourni la grande partie des renseignements desquels dépend le développment de plans hydrologiques. Il nous faut encore de renseignements pour mieux comprendre les effets générateurs du drainage de surface des eaux d'orage. Il faut étudier davantage ce que la quantité de certains types différents de parties isolées des bassins pourraient nous enseigner à propos des combinaisons variées d'influences géologiques, végétales, et terrestres. Ces combinaisons réagissent réciproquement pour déterminer les caractéristiques du drainage des inondations dans les parties isolées (*sub-areas*) des bassins qui sont significatives du point de vue hydrologique.

Nous souhaitons également de meilleurs renseignements sur les caractéristiques suivantes des pluies convectionnelles : la durée, la quantité, du terrain. Ces renseignements sont importants surtout que les caractéristiques varient selon les influences localement orographiques, et selon la région géographique. Le peu que nous avons pu

apprendre des régions dispersées dans les Etats-Unis indique que les renseignements actuels sur la pluviosité pour prédire la quantité de drainage de surface des inondations sont insuffisants.

Pour développer des méthodes plus précises et plus practicables afin de dissiper le drainage superficiel des inondations dans les parties les plus proches des lignes de partage des eaux—en dirigeant l'eau par des systèmes complexes de canaux naturels pour la synthèse hydrographique des inondations d'aval—il y a grand besoin d'encore de recherche sur la coulée hydraulique. Des études sur cet aspect de l'hydrologie de la prediction du drainage de surface des inondations sont actuellement en cours.

Une connaissance plus profonde est nécessaire pour développer des méthodes hydrologiques fondamentales pour la disposition et le plan des moyens de protection contre les inondations d'amont, de systèmes correspondants d'irrigation, de drainage, et d'autres améliorations pour les petits bassins dans les Etats-Unis. Ces besoins sont en train d'attirer l'attention et de diriger les efforts d'hydrologues, de météorologistes, d'hydrauliciens, de géologues, et des experts dans la science du sol et de flore. Dans ce programme d'études compréhensives sur les bassins, il faut encore beaucoup de travail de recherche.

INTRODUCTION

The watershed has long been recognized as the most effective unit for planning of land and water resources protection and development. A relationship between streamflow and watershed conditions was recognized as early as 1892 and this concept entered into the justification for creating the National Forest Reserve. Other Federal legislation along these lines followed, and the Flood Control Act of 1936 provided for general Federal participation in programs for runoff and water flow retardation and soil erosion prevention on the watersheds of the Nation's rivers and waterways.

The Watershed Protection and Flood Prevention Act, Public Law No. 566, 83rd Congress, is the latest Federal legislation relating to upstream watershed programs. This Act of 1954 and subsequent amendments authorize the Secretary of Agriculture to co-operate throughout the Nation with state agencies and local improvement districts operating under state laws in planning and carrying out upstream watershed projects for flood prevention, protection of watershed lands, development and utilization of water resources, and disposal of excess waters.

The ensuing discussion considers hydrology research needs for support of a nationwide upstream flood prevention and related watershed development program.

UPSTREAM PROGRAM NEEDS AND PROGRESS

A Conservation-Needs Inventory by the U. S. Department of Agriculture, Soil Conservation Service, delineated nearly 12,000 watersheds of a size suitable for projects under PL-566([1]). These are watersheds up to 250,000 acres or about 400 square miles in area. Approximately 8,300 such watersheds, encompassing nearly a billion acres, or half the land area of the United States, were considered to need project action. About three-fourths of the problem watersheds were reported to need protection from flood water and associated sediment damages. However, many of these watersheds need *multipurpose* projects for their best protection and utilization. Additional upstream watershed improvement needs include domestic and irrigation water supplies, drainage, recreation, fish and wildlife, low-flow regulation for pollution abatement.

Nearly 4,000 of the problem watersheds need drainage for 45 million acres ; 2,600 need irrigation facilities to benefit 14 million acres. The latter refers to irrigation in the valleys of upstream watersheds, and does not include many more millions of acres needing irrigation improvement to utilize water from major reclamation projects. The drainage and irrigation problems of millions of acres in small valleys are closely related to storm runoff from the immediately surrounding uplands—either too much or too little runoff, or its unfavourable time distribution.

As of April 1, 1962, 56 million acres, or about 6% of the watershed lands needing projects, had been authorized for work under PL-566 and earlier upstream flood control acts. Projects now authorized for planning would raise this figure to about 8%([2]). Only a small fraction of the needed watershed improvement and projection planning and design has yet been done. The more complex situations, especially those involving closely related problems of drainage or water supplies, or both, along with flood runoff control and sedimentation problems, will increase demands for research information on which to base adequate watershed management planning, and engineering design of control structures.

DOWNSTREAM IMPLICATIONS

Not only may there be concern for several interrelated problems within the tributary watersheds for which projects are being planned, but if such projects are carried out on *many* such tributaries to a major stream, they might have significant combined effects, far downstream. Not all such effects might be beneficial.

([1]) Williams, D. A., "Soil and Water Conservation Needs Inventory," Proceedings Eighth National Watershed Congress, Tucson, Arizona, April 1961.

([2]) U. S. Soil Conservation Service, Information Division, letter to the writer, April 13, 1962.

It is conceivable that watershed projects involving extensive land treatment measures to increase rainfall infiltration, and upstream reservoirs to retain flood flows, might reduce the water supply for downstream uses. There may also be a question as to whether longer-sustained stream flows from upstream reservoir releases will swamp lowlands. Or, if the flood water is retained in reservoirs upstream, will ground-water levels fall disasterously in the downstream valleys ? Will sustained bank full flows from reservoir releases result in increased stream bank erosion and channel meander, downstream ? Or will channels degrade under flows having reduced sediment loads ?

While downstream effects of upstream watershed projects might, as pointed out, not be all desirable, adequate planning and design of overall programs on major stream systems may result in important downstream benefits. Frequency and severity of floods may be reduced, and sustained low flows at desirable levels may provide needed water supply diversion and storage downstream for agricultural, industrial, and domestic uses, and for stream pollution control. These are complex planning and design problems that will become increasingly important as watershed projects are developed on more and more upstream tributaries.

FLOOD PREDICTION

In developing watershed management plans, it is necessary to consider the total hydrology of the project watershed and associated sedimentation and hydraulic design problems. Where numerous tributary watersheds are involved, their combined effect upon the flow regime downstream must also be taken into account. Basic to these planning and design problems is the predicting of storm runoff, considering climatic factors, land use and treatment, and various watershed physical characteristics.

The U. S. Soil Conservation Service has done a difficult and a very creditable job of evolving improved procedures for flood runoff prediction, based on limited available basic hydrologic information([3]). Some information used has come from small-plot experiments, designed for other purposes. Such plot experiments have been carried out under both natural and artificial rainfall. Much information has also come from approximately 300 small agricultural watersheds. They range from a few acres to a few square miles in area. Rainfall, runoff, and other data have been collected from these experimental watersheds for varying periods during the past 25 years, by the former soil Conservation Service, Research Division, and since 1954, by the Soil and Water Conservation Research Division of the Agricultural Research Service, U. S. Department of

([3]) USDA, Soil Conservation Service, "Engineering Handbook, Supplement A, Hydrology."

Agriculture. Thirty years of plot and small watershed research data obtained by the U. S. Forest Service have also been used.

Within the past 8 years the Agricultural Research Service initiated hydrologic studies on a few larger watersheds, in the 50 to 100 square-mile class, on farm and nonforest rangelands ; and the Forest Service has underway limited similar watershed experiments in the forest and forest-associated range areas.

More extensive and conclusive data are urgently needed to adequately predict flood runoff from watersheds up to 400 square miles in area throughout the United States, under widely varying conditions of climate, physiography, and land-use and treatment. There is even less basis for predicting the *downstream* consequences of projects in tributary watersheds.

RESEARCH NEEDS

How can the urgently needed answers to increasingly complex and comprehensive upstream flood hydrology problems be found? Rainfall-site influences on runoff generation can be evaluated by closely controlled, small-area experiments. However, site influences in relation to watershed runoff are confounded by numerous runoff transmission phenomena. That portion of the flood runoff prediction problem, in itself, presents several unknowns. Small-plot and lysimeter data, including those obtained with artificial rainfall applicators, can be useful in predicting flood runoff from natural watersheds, but not by simple, direct methods. Data of that kind which we now have, will be further applicable when we not only better understand the fundamental runoff generative processes, but also have benefit of more watershed-measurement data to know how these and other fundamental hydrologic processes are integrated in complex watershed behaviour.

Data now available must definitely be supplemented by additional basic information in four major areas:

1. *Precipitation phenomena* and their influences on watershed runoff.
2. *Mechanics of surface runoff generation.*
3. *Geologic influences on flood runoff.*
4. *Hydraulics of flood runoff*—overland and in complex channel systems.

SITE INFLUENCES

For adequate understanding of the mechanics of on-site runoff generation, additional well-designed and closely controlled laboratory and small-plot, and small-watershed experiments are needed, with more precise and complete instrumentation than has been possible in the past. Such experiments are needed to determine both the effects

of varying *surface-influence* factors on the runoff generative process, *e.g.*, soil-plant influences, and the soil and geologic *influences below the surface.*

In addition to such fundamental research, test data are also needed to characterize and group the hundreds of recognized soil type in terms of their runoff influence and to evaluate for each hydrologic soil category such modifying effects as erosion, plant cover, soil management and antecedent soil moisture levels. These types of information are needed to more precisely estimate the runoff generative potentials of watershed lands, relative to known or assumed precipitation characteristics.

PRECIPITATION PATTERNS

Needs for data on precipitation-site influences on runoff have been discussed first because of their relation to much of the existing data and current research effort. Otherwise, a logical starting point for this discussion of research needs for improved flood runoff prediction would have been the needs for basic data on precipitation itself. The site-influences data can be of value for estimating runoff only to the extent that they can be coupled with good estimates of several important parameters of precipitation. Much additional data is needed on snow accumulation and melt factors, as snowmelt may contribute to upstream floods. However, the most urgent need is for information on intense thunderstorm rainfall.

For the most part, flood runoff from watersheds of sizes within the purvey of PL-566, is generated by intense, convectional-type storms. These storms are usually of very limited areal extent, and are highly variable over their area of coverage with respect to both rainfall depth and intensity. While rainfall has been generally characterized for various parts of the country by long-period records of the U. S. Weather Bureau, the gage networks have not been of sufficiently dense coverage to determine the areal distribution characteristics or the expectancies of intense thunderstorms for a given area of 400 square miles or less, in many areas of the United States.

Probably the greatest geographic variability of intense rainstorms is in the arid and semi-arid areas of the West, where rainfall records are most sparse and of comparatively short experience. Keppel([4]) reports on a record storm measured in 1960 by a network of recording raingages of about one gage per square mile, over the approximately 70-square-mile area of the Alamogordo Creek Experimental Watershed in New Mexico. This is a watershed under comprehensive study by the Agricultural Research Service. He states: "Experience with dense rain gage networks at this and other watersheds of comparable size in New Mexico and Arizona has shown that

([4]) Keppel, R. V., "A record storm event on the Alamogordo Creek Experimental Watershed in Eastern New Mexico. June 5, 1960," presented at American Geophysical Union meetings, Washington, D.C., April 1961.

the probability of recording a given maximum rainfall in one member of the network is considerably greater than that the same value will be recorded at a given point. Thus, with networks having gage spacings approximating the storm diameters, it is not unusual to find that the 50-or 100-year return period values, based on the long-term record of a nearby station, are exceeded at one or more points in the network during the first three or four years of observation."

The record Alamogordo Creek storm in 1960, reported by Keppel, produced intensities of rainfall for durations up to more than 25 minutes which exceeded any of previous record in the United States. Yet practically the same intensities for durations up to 15 minutes were measured again in a storm over the same watershed in 1961, at a point approximately 2 miles from the centre of the preceding year's record. In both cases the intensities exceeded by several times those estimated for the 100-year point-rainfall expectancy, based on the nearest Weather Bureau recording gages, several miles distant in various directions from this watershed.

Fletcher ([5]) reports on 5 years of record from a similar dense network of recording raingages, on the Walnut Gulch Experimental Watershed or the Agricultural Research Service in Southeastern Arizona. He demonstrated that convective storm systems, that is, rain associated with general wet air masses moving over the watershed, produced on this watershed one or more *raincells* randomly separated in time and space. Eighty per cent of 811 such cells measured were less than 4·5 square miles in area, or had a mean diameter of a little over 2 miles. Of the storm systems over the 57-square-mile area of the watershed, practically 50% included only one raincell and less than 20% included more than three. No single raincell in convectional storms measured in that 5-year period covered more than 20 square miles. However, a maximum 24-hour rainfall of a little over 5 inches was recorded at one gage, compared with an estimated 100-year expectancy of point-rainfall for the vicinity of 3·84 inches, based on a 61-year record.

Indications of observed severe storm effects, and of present limited experience with a few dense raingage networks, cast serious doubts on existing knowledge of rainfall characteristics affecting run-off probabilities from upstream watersheds. To predict floods adequately for thousands of watersheds over the United States will require substantially more information than now exists on convectional storm characteristics, as they vary regionally and with local orographic influence. The Agriculture Research Service is beginning to get a sampling with the few dense gaging networks installed in the past few years on its experimental watersheds in Arizona, New Mexico, and Idaho. Additional such networks are now being installed in Oklahoma and in South Dakota. More dense raingage

([5]) Fletcher, Joel E. "Some properties of precipitation associated with runoff from Walnut Gulch Watershed, Arizona." Presented at American Geophysical Union meetings, Washington, D.C., April, 1961.

networks are needed in the West for sampling of additional climatic zones and study of local influence factors. Probably similar sampling is needed in the Eastern United States. Certainly, records indicate that the most intense storms in the country occur in the Gulf and Southern Atlantic Seaboard States.

Cost of installation and operation of sufficiently dense recording raingage networks is prohibitive for early adequate sampling over the entire U.S. Some prospect may be in the offing, however, for feasible broader application of *radar* techniques to this problem. It is hoped that there may be early breaks-through in development of radar equipment and techniques by the Weather Bureau and others now working on the problem, to soon enable adequate direct measurement of time-depth-area patterns for convectional-type storms.

HYDROGRAPH SYNTHESIS

If information is at hand to predict the area-time-depth pattern of a design storm system, it can be variously positioned over the project watershed for study of its runoff-producing capabilities. Based on the season of the year for such an expected storm and some knowledge of the correspondingly probable antecedent rainfall, vegetation, soils, geology, and land treatment practices, estimates can be made of the runoff-generative potentials of various sub-areas of the watershed covered by the storm system.

With an estimate of net design supply thus developed, the next problem is to translate the resulting surface runoff to a flood hydrograph at some point downstream. Many phenomena are involved between the point of generation of surface runoff and its appearance as runoff at a downstream point. Some surface runoff will be lost enroute. On the other hand, some of the water appearing as floodflow in the stream may not have started out as surface runoff, but as rainfall that entered the soil surface where it fell and moved laterally over some impeding substratum, to reappear as surface runoff at a lower elevation. To relate excess on-site rainfall to downstream flood runoff requires understanding of many aspects of watershed hydrologic behavior and good knowledge of both the surface and sub-surface physical character of the particular watershed under consideration.

Surface phenomena: Consider first the runoff from a relatively small watershed, may be a few acres, which can be considered as a basic hydrologic entity. It will represent a single, hydrologically significant combination of soils, vegetation, and geology, and will generally be subject to essentially uniform rainfall. This has been referred to in research terminology as a *unit-source* watershed. On-site rainfall excess moving from its point of occurrence to the outlet of the unit-source watershed involves a transit time-lag. The outflow hydrograph is also modified in shape by the successive build-up and depletion of temporary storage on the land surface and in the stream

system. Some adjustment may also be required in synthesis of the hydrograph of the unit-source watershed for unrecoverable storage in land-surface depressions. Data from varying types of experimental unit-source watersheds are needed to provide adequate basis for estimating these modifying watershed-surface effects on the outflow hydrograph. Rather approximate methods are now generally used. These approximations may have important effects on the synthesized hydrograph of combined downstream flows from several such elemental unit-source watersheds.

Subsurface phenomena : Another set of influences on both the runoff supply and geometry of the unit-source hydrograph relates to subsurface characteristics of the watershed. Both the volume of the flood and the shape of its hydrograph may be strongly influenced by the reappearance at the surface of rainfall that initially entered the soil ; or conversly, by downstream abstractions from the intial surface runoff as it passes over exposed aquifer surfaces, such as sand, gravel, or fractured rock. It has been commonly considered that the interflow between surface and subsurface waters was not an important factor affecting storm runoff from upstream watersheds, and accordingly that such runoff could be adequately estimated in relationship only to rainfall, less on-site abstractions. This is in many cases a false premise, and the present methods of flood prediction are quite inadequate for many situations, because of a void in information on subsurface influences, or what has been termed aquifer-streamflow relations.

In many places in the humid section of the country, part of the rainfall originally penetrating the soil surface reappears as surface runoff within a short distance, hundreds of feet or less. On many steep upstream mountain and foothill watersheds in the West with shallow, but highly permeable soils over highly fractured geologic materials, there is little evidence of appreciable overland runoff. Yet, storm-associated floods occur in their valleys. Definite answers are not known to many questions regarding flow of rainwater into and through the soil and upper geologic materials which may contribute to flood runoff from watersheds of 400 square miles or less.

What is known about water penetration into the land surface is limited by the fact that experimental techniques commonly used have restricted the rates at which artificial rainfall was applied. Kinetic energy applied, pressures developed, and the degree of coverage of the surface with water were not comparable to what happens under rainfall intensities of 6, 8, 10, or may be even 20 inches per hour. The needed information on sub-surface influences on runoff generation must come from studies of hydrographs of natural unit-source watersheds, typifying hydrologically significant geologic-soil complexes.

Conversely to contributions from subsurface out-flows, even more profound geologic effects on flood runoff may be the disappearance of surface runoff into the underground. This occurs in cavernous limestone areas, and it occurs extensively in sand-and gravel-bed

stream channels in the arid West. Keppel[6] reports channel absorption of storm flows amounting to more than 20 acre-feet per mile on the Walnut Gulch Experimental Watershed at Tombstone, Arizona. He estimates that, for higher flood peaks expected, maximum transmission losses in various channel reaches within that 57-square-mile watershed may range between 40 and 80 acre-feet per mile, at rates of up to about 5 acre-feet per mile, per hour. This phenomenon affects both flood peaks and the shape of the flood hydrograph most preversely, actually reversing the usual trends of flood duration and peak rates in relation to watershed size, as compared with humid area streams. Floods occurring downstream in arid areas are generally substantially diminished from their upstream magnitudes, and many upstream flood flows are lost completly within a few miles. Research, tracing of floods through channel systems as they emanate from various tributary areas and from varying portions of the total watershed, on this and other 50-to 100-square-mile experimental watersheds in the Western states, is now beginning to yield some highly important information on this major mitigating influence on flood runoff. More information of this type will be needed from other experimental watersheds, representing ranges of channel materials, underlying geology and climate.

FLOOD ROUTING

After synthesizing the hydrographs of unit-source watersheds, the next problem confronting the design hydrologist is translocating or routing them through lower channel reaches as they *combine* with the flow from other parts of the basin, to devise the hydrograph for a downstream location where the construction of runoff control works is under consideration. The engineer is generally concerned not only with having a good estimate of the expected design flood peaks but needs a reasonably good definition of the geometry of the entire flood hydrograph, to route it through the proposed reservoir and come up with a safe, effective and economical balance of spillway capacity and reservoir flood storage. Also, if he plans to release flows from several reservoirs on a major stream system, he will need to determine how they will combine, together with the runoff from uncontrolled areas in the basin, to affect flows downstream.

Many approximation methods have been devised for flood routing and several are in common use. There is little experimental data for development of really precise routing procedures, especially with such confounding influences as high and fluctuating rates of transmission loss as occur in arid area streams. Limited basic information exists for design of mathematical models for computing more precise flood routings. Also, the complexity of computational procedures that would be involved, and the necessity for repetitive solutions to route flows from numerous tributaries and to combine them, step by step, as they move through complex channel systems,

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[6] Keppel, R.V., "Transmission losses in Ephemeral Sand-Gravel Bed Streams in the Arid West," Proc. ASCE, v 88, n HY3, May 1962.

have discouraged development of better methods. Now, however, with high-speed electronic computors, and photogrametric methods for accomplishing more detailed channel surveys becoming available, utilization of improved routing procedures is rapidly becoming much more feasible.

There is need for research to devise and test new routing methods, and to compile information on channel hydraulics for their effective use. The Agriculture Research Service has recently initiated comprehensive hydrologic studies on larger experimental watersheds that will provide opportunity for research in this area. Development of improved flood routing information and techniques will be a major objective of its Southern Plains Regional Watershed Research Centre, working in the Washita River Basin in Oklahoma. Work is also uuderway in the Northwest on application of electric analog devices to routing problems; and in the Southwest, special attention is being given to study of runoff hydraulics associated with flash runoff from steep lands and through steep channels, involving high-velocity, momentum-wave travel.

CONCLUSIONS AND RECOMMENDATIONS

The objective of this presentation has been to highlight some of the hydrology research needs in connection with upstream flood prevention programs. It has been pointed out that possibly half of the land area of the United States may eventually be involved in over 8,000 separate upstream watershed projects. Less than 10% of the planning and design work needed for these watersheds is completed or underway. As more effort is directed to development of multipurpose projects, more complex and difficult planning and design problems will create added and intensified demands for more and better research information on which to base flood runoff prediction. Reliable estimates of the hydrograph geometry and volume expectancies of flood runoff are necessary to plans and designs for its control and utilization.

Additional precise, small-area experiments are needed for more conclusive information on fundamental hydrologic processes. Such studies should be planned and conducted in close co-ordination with an overall hydrology research program. Much additional information is also needed on precipitation characteristics, on watershed subsurface influences, and on the hydraulics of overland and channel flows. These latter items of research must be accomplished on a watershed basis. They must consider behavior of various types of unit-source watersheds, and the advance of flows, combining from several unit-source watersheds, through complex stream channel systems. Such studies must include watersheds of sufficient size that many factors affecting the relation of floods to watershed size become stabilized, and the remaining influences of size are *simply* predictable.

Improved equipment and techniques for physical measurements, data processing, and analysis may aid materially in solution of the many complex problems involved. However, the problems of flood runoff and the practical aspects of accomplishing their solution will continue to challenge the minds of hydrologists, meteorologists, hydraulicians, geologists, and plant and soil scientists for some years to come.