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WORLD METEOROLOGICAL ORGANIZATION

Operational Hydrology
Report No. 1

MANUAL FOR ESTIMATION OF PROBABLE MAXIMUM PRECIPITATION

1873 1973
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NOTE

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FOREWORD

Having in mind the need for guidance material on the procedures for estimating probable maximum precipitation for hydrological forecasting and design purposes, the president of the Commission for Hydrology and the WMO Executive Committee Panel of Experts for the International Hydrological Decade recommended that a manual be prepared describing the techniques that have been found generally applicable in middle latitudes for basins of various sizes subject to both orographic and non-orographic effects.

Arrangements were accordingly made by WMO for the preparation of this report. It has been written by J. L. H. Paulhus, consulting hydrometeorologist in co-operation with the Office of Hydrology, National Weather Service, National Oceanic and Atmospheric Administration, U.S. Department of Commerce. Principal contributors from that office were J. F. Miller, J. T. Riedel, F. K. Schwarz and C. W. Cochrane. Portions of the text were taken from material written by V. A. Myers.

I should like to express the gratitude of WMO to Mr. J. L. H. Paulhus and to those of his colleagues who contributed to this excellent report on a very complex subject, which is now published as the first of a new series of WMO publications entitled "Operational Hydrology".

D. A. Davies
Secretary-General

SUMMARY

Probable maximum precipitation (PMP) is defined as the greatest depth of precipitation for a given duration meteorologically possible for a given basin at a particular time of year, with no allowance made for long-term climatic trends. Current knowledge of storm mechanisms and their precipitation-producing efficiency is inadequate to permit precise evaluation of limiting values of extreme precipitation. PMP estimates must be considered therefore, at least for the present, as approximations. The accuracy, or reliability, of an estimate depends basically on the amount and quality of data available for applying various estimating procedures.

Procedures for estimating PMP cannot be standardized as they vary with amount and quality of data available, basin size and location, basin and regional topography, storm types producing extreme precipitation, and climate. There are many regions in various parts of the world for which PMP has never been estimated. It would be impossible at this time to prepare a manual that would cover all problems that might possibly be encountered. Nor would it be practicable to prepare a manual that would cover all situations that have arisen in deriving past estimates. For these reasons, this manual discusses procedures that have been found generally applicable in the middle latitudes for basin sizes up to about 50 000 km^2 in orographic and non-orographic regions.

The procedures are described by examples from actual studies by the National Weather Service (formerly U.S. Weather Bureau), National Oceanic and Atmospheric Administration, U.S. Department of Commerce. Several countries have made equally valid studies. The chief reasons for using the examples described were that: (1) they represented a variety of problems, (2) they were from studies published in widely distributed reports relatively accessible for reference, and (3) ready availability of basic material, such as photographic prints of many illustrations, minimized time and cost of preparing this manual. The examples given cover estimates for specific basins and generalized estimates, and include PMP estimates for thunderstorms, general storms, and tropical storms.

All procedures described except one are based on the meteorological, or traditional, approach. The one exception is a statistical procedure. The traditional approach consists essentially of moisture maximization and transposition of observed storms. Wind maximization is sometimes used. Storm transposition involves adjustments for elevation, moisture-inflow barriers, and distance from the moisture source. These adjustments are founded on hypothetical storm models. A variation of the traditional approach is the use of an orographic computation model in mountainous regions. Methods are described for determining the seasonal variation and chronological and areal distribution of PMP.

Tables of precipitable water in a saturated pseudo-adiabatic atmosphere are included for making various adjustments involving atmospheric moisture. Also included are world record and near-record rainfalls that may be used for making rough assessments of derived PMP estimates.

SUMMARY

The manual was written under the assumption that the user would be a meteorologist. No attempt was made to define or discuss basic meteorological terms or processes. It is believed that the procedures described are presented in sufficient detail to permit the professional meteorologist, especially one with hydrological training and ingenuity, to proceed with their application to the usual problems involved in estimating PMP.

RESUME

La hauteur maximale probable des précipitations (HMPP) est définie comme étant la hauteur maximale de la lame d'eau qui peut météorologiquement s'accumuler en un temps donné, sur un bassin donné, à une époque déterminée de l'année, sans qu'il soit tenu compte des tendances climatiques à long terme. Nos connaissances actuelles sur le mécanisme des perturbations et sur la quantité de précipitations que celles-ci peuvent effectivement donner sont insuffisantes pour nous permettre d'évaluer avec précision les valeurs extrêmes des précipitations exceptionnelles. Les estimations de la HMPP doivent donc être considérées, tout au moins pour le moment, comme des approximations. L'exactitude, ou la fiabilité, d'une estimation dépend fondamentalement de la quantité et de la qualité des données dont on dispose pour appliquer les diverses méthodes d'estimation.

Il n'est pas possible de normaliser les méthodes employées pour estimer la HMPP étant donné qu'elles varient en fonction de la quantité et de la qualité des données disponibles, de la superficie et de la situation du bassin, des caractéristiques géographiques du bassin et de la région, de la nature des perturbations responsables des précipitations extrêmes et, finalement, du climat. Dans diverses parties du monde, il existe de nombreuses régions pour lesquelles la HMPP n'a encore jamais été estimée. Il serait impossible actuellement d'établir un manuel qui traite de tous les problèmes susceptibles de se poser. Il n'est pas possible non plus de préparer un manuel qui fasse état de toutes les situations rencontrées dans le passé lors de l'établissement d'estimations de la HMPP. Pour ces raisons, le présent manuel analyse les méthodes qui se sont révélées généralement utilisables aux latitudes moyennes pour des bassins d'une superficie égale ou inférieure à 50.000 km^2, en région montagneuse et en région de plaine.

Ces méthodes sont exposées en recourant à des exemples d'études réellement faites par le service météorologique national (anciennement le U.S. Weather Bureau), l'Administration nationale de l'océan et de l'atmosphère et le ministère du Commerce des Etats-Unis. Plusieurs autres pays ont effectué des études tout aussi valables. Les principales raisons qui ont motivé le choix des exemples retenus sont : 1) ceux-ci correspondent à différentes sortes de problèmes, 2) ils sont tirés d'études qui ont été publiées dans des rapports largement diffusés qu'il est assez facile de se procurer si l'on veut s'y référer, et 3) le temps de préparation du manuel et les frais d'impression de celui-ci ont été réduits du fait que l'on disposait du matériel nécessaire, par exemple des clichés photographiques d'une grande partie des illustrations. Les exemples donnés concernent des estimations établies pour des bassins particuliers et des estimations de caractère général; ces exemples comprennent des estimations relatives à la hauteur maximale des précipitations engendrées par des orages, par des perturbations de type classique et par des tempêtes tropicales.

A une exception, toutes les méthodes exposées sont fondées sur la technique météorologique dite traditionnelle. La seule exception concerne une méthode statistique. La technique traditionnelle consiste essentiellement à maximiser le contenu en vapeur d'eau et à extrapoler en partant des averses observées. On a parfois recours également à la maximalisation du vent. L'extrapolation à partir des averses observées nécessite de tenir compte de l'altitude, des barrières s'opposant au transport de la vapeur d'eau et de l'éloignement du lieu par rapport à la source de vapeur d'eau. Les ajustements apportés pour tenir compte de ces paramètres sont fondés sur des modèles hypothétiques des averses. Une variante de la technique traditionnelle consiste à utiliser, dans les régions montagneuses, un modèle de calcul orographique. Le manuel expose diverses méthodes pour déterminer la variation saisonnière ainsi que la distribution spatio-temporelle de la HMPP.

Des tableaux de l'eau précipitable au sein d'une atmosphère pseudo-adiabatique saturée ont été inclus pour permettre d'effectuer divers ajustements en ce qui concerne le contenu de l'atmosphère en vapeur d'eau. Le manuel comporte également une liste de valeurs record et quasi record de la hauteur des précipitations qui peut servir à évaluer grossièrement les estimations de la HMPP obtenues.

Le manuel a été rédigé à l'intention des météorologistes. Il n'a donc pas été jugé nécessaire de définir et d'expliquer les termes et les processus météorologiques fondamentaux. On estime que les méthodes décrites sont exposées suffisamment en détail pour que les météorologistes, pour peu qu'ils soient ingénieux et qu'ils aient reçu une formation hydrologique, puissent les appliquer pour résoudre les problèmes courants que pose l'estimation de la HMPP.

РЕЗЮМЕ

Вероятные максимальные осадки определяются как наибольший слой осадков за данную продолжительность, метеорологически возможную для данного бассейна в определенное время года без учета долгосрочных климатических тенденций. Существующие знания механизмов циклонов и их ливнеобразующей эффективности недостаточны, чтобы позволить произвести точную оценку экстремальных осадков. В связи с этим оценка вероятных максимальных осадков, по крайней мере в настоящее время, должна рассматриваться как приближенная. Применение различных процедур для определения точности или надежности оценки зависит в основном от объема и качества имеющихся данных.

Методы оценки вероятных максимальных осадков не могут быть стандартизированы, так как они изменяются в зависимости от объема и качества имеющихся данных, размера и географического положения бассейна, топографии бассейна и района, характера штормов, дающих экстремальные осадки, и климата. В различных частях земного шара существует много районов, для которых никогда не производился расчет вероятных максимальных осадков. В настоящее время было бы невозможно подготовить пособие, охватывающее все проблемы, которые могут быть встречены. Было бы также невозможно подготовить пособие, которое охватывало бы все ситуации, которые возникали при выведении оценок в прошлом. По этим причинам в настоящем пособии рассматриваются методы, которые, как правило, были признаны применимыми в средних широтах для бассейнов размерами примерно до 50 000 км^2 в горных и равнинных районах.

Методика описывается с помощью примеров фактических исследований, проведенных Национальной метеорологической службой (ранее Бюро погоды США), Национальное управление по океану и атмосфере, Департамент торговли США. В нескольких странах были проведены аналогичные исследования. Описанные примеры использовались по следующим причинам: (1) в них представлены различные проблемы, (2) они взяты из исследований, которые были описаны в широко распространенных докладах и которые легко могут использоваться для ссылок, (3) легко можно получить основной материал, такой как фотографические отпечатки многих иллюстраций, что ускорило и удешевило подготовку настоящего пособия. Приведенные примеры охватывают оценки по конкретным бассейнам и обобщенные оценки и включают оценки вероятных максимальных осадков для гроз, обычных ливней и тропических ливней.

Все описанные способы, за исключением одного, основываются на метеорологическом, или традиционном подходе. Единственным исключением является статистический метод. Традиционный метод состоит в основном в максимизации влагосодержания и транспозиции наблюдаемых ливней. Иногда используется и максимизация ветра. Транспозиция ливня предусматривает учет высоты препятствия для притока влаги и расстояния от источника влаги. Методы учета этих факторов получены на основе гипотетических моделей ливней. Вариантом традиционного подхода является применение орографической модели расчета в горных районах. Описываются методы для определения сезонных изменений и распределения вероятных максимальных осадков во времени и по площади.

Для учета различных факторов, касающихся атмосферной влаги, приводятся таблицы общего количества пара в насыщенной псевдоадиабатической атмосфере, которое может выпасть в виде осадков. В пособие включены также мировые рекордные или близкие к рекордным осадки, которые могут использоваться для грубой проверки расчетных значений вероятных максимальных осадков.

Пособие составлено в расчете на то, что им будут пользоваться метеорологи. Основные метеорологические термины и процессы не определяются и не обсуждаются. Предполагается, что методы описаны достаточно подробно, чтобы позволить профессиональному метеорологу, в особенности метеорологу, прошедшему подготовку по гидрологии, применять эти методы к обычным проблемам, касающимся оценки вероятных максимальных осадков.

RESUMEN

La precipitación máxima probable se define como la mayor cantidad de precipitación meteorológicamente posible que corresponde a determinada duración en una cuenca dada y en determinada época del año, sin tener para nada en cuenta las tendencias climáticas que se producen a largo plazo. Los conocimientos que actualmente se poseen sobre el mecanismo de los temporales y su eficacia para producir precipitaciones resultan insuficientes para poder evaluar con precisión los límites de los valores extremos de la precipitación. Las estimaciones de la precipitación máxima probable han de ser pues consideradas, al menos por el momento, como aproximaciones. La precisión y seguridad de una estimación depende fundamentalmente de la cantidad y calidad de los datos disponibles para su aplicación a los diferentes procedimientos de estimación.

Los procedimientos de estimación de la precipitación máxima probable no pueden ser normalizados ya que varían con la cantidad y calidad de los datos disponibles, con el tamaño de la cuenca y su emplazamiento, con la topografía de la cuenca y de la región, con los tipos de temporales que producen precipitaciones extremas y con el clima. Existen numerosas regiones en varias partes del mundo en las que jamás se ha estimado la precipitación máxima probable. Sería imposible en este momento redactar un manual en donde se estudiaran todos los problemas que a este respecto pueden plantearse. Tampoco sería factible resumir en un manual todas las situaciones que se plantearon al deducir las estimaciones anteriores. Por estos motivos, en el presente Manual se estudian los procedimientos que se consideran de aplicación general en las latitudes medias en las cuencas cuya extensión sea de hasta 50.000 km^2 aproximadamente, en regiones montañosas y llanas.

Los procedimientos se describen en forma de ejemplos tomados de los estudios reales llevados a cabo por el Servicio Meteorológico Nacional de Estados Unidos de América, dependientes de la Administración Nacional del Océano y de la Atmósfera, del Departamento de Comercio. Varios países han efectuado también valiosos estudios. Las principales razones que han motivado la utilización de los ejemplos antes descritos son los siguientes: 1) estos ejemplos representan diferentes problemas; 2) han sido tomados de estudios publicados en informes de amplia distribución que resultan de acceso bastante fácil para usarlos como referencia; y 3) fácil disponibilidad de la documentación básica, tal como las fotografías de numerosas ilustraciones y reducción al mínimo de los gastos y tiempo necesarios para la preparación de este Manual. Los ejemplos citados se refieren a estimaciones para determinadas cuencas así como de carácter general y en ellos se incluyen valores estimados de la precipitación máxima probable procedente de las tormentas, de los temporales en general y de las tormentas tropicales.

Todos los procedimientos descritos, excepto uno, están fundados en planteamientos meteorológicos o tradicionales. La única excepción es el procedimiento estadístico. El planteamiento tradicional consiste fundamentalmente en la maximización de la humedad y en la transposición de los temporales observados. Algunas veces se

utiliza también la maximización del viento. La transposición de los temporales implica ajustes de altitud, de las barreras contra el flujo de humedad entrante y de la distancia a partir de la fuente de humedad. Estos ajustes se fundan en modelos de temporales hipotéticos. Una de las variaciones del planteamiento tradicional consiste en la utilización de un modelo orográfico de cálculo, aplicable en las regiones montañosas. Se describen métodos para determinar la variación estacional y cronológica así como la distribución zonal de la precipitación máxima probable.

Se incluyen también tablas de agua precipitable en una atmósfera saturada pseudoadiabática, con objeto de hacer varios ajustes en los que interviene la humedad atmosférica. También se incluye un registro mundial y un registro aproximado de la lluvia que pueden ser utilizados para hacer evaluaciones no muy aproximadas de las estimaciones deducidas de la precipitación máxima probable.

Este Manual ha sido escrito suponiendo que el usuario es meteorólogo. No se ha tratado de definir o discutir los términos o procesos meteorológicos. Se cree que los procedimientos descritos han sido expuesto con detalle suficiente para que el meteorólogo profesional, especialmente con formación hidrológica y dotado de cierta iniciativa, pueda aplicarlos a los problemas habituales que se plantean para estimar la precipitación máxima probable.

CHAPTER 1

INTRODUCTION

1.1 Definitions of probable maximum precipitation (PMP)

1.1.1 Conceptual definition

The use of meteorological knowledge to derive limiting precipitation values for hydrological design purposes began to gain favour in the middle 1930's. There are varying degrees of limiting design values depending on the purpose for which they are required. Precipitation associated with the uppermost limits is known as the probable maximum precipitation (PMP), which is defined /1/ as the theoretically greatest depth of precipitation for a given duration that is physically possible over a particular drainage basin at a particular time of year. Such is the conceptual definition of PMP. The values derived as PMP under this definition are subject to change as knowledge of the physics of atmospheric processes increases. They are also subject to change with long-term climatic variations, such as would result from changes in solar radiation intensity. Climatic trends, however, progress so slowly that their influence on PMP is small compared to other uncertainties in estimating these extreme values. Climatic trends are therefore ignored.

1.1.2 Operational definition

In addition to the conceptual definition of PMP, an operational definition may be considered as consisting of the steps followed by hydrometeorologists in arriving at the answers supplied to engineers for hydrological design purposes. Whatever the philosophical objections to the concept, the operational definition leads to answers that have been examined thoroughly by competent meteorologists and engineers and judged as meeting the requirements of a design criterion. The result of applying the operational definition over an entire region is to approach uniformity in design, safety and cost.

1.1.3 Maximum possible precipitation

Probable maximum precipitation (PMP) was once known as maximum possible precipitation (MPP), and this latter term is found in most reports on estimates of extreme precipitation made prior to about 1950. The chief reason for the name change to PMP was that MPP carried a stronger implication of physical upper limit of precipitation than does PMP, which is preferred because of the uncertainty surrounding any estimate of maximum precipitation. Procedures for estimating PMP, whether meteorological or statistical, are admittedly inexact, and the results are approximations. Different, but equally valid, approaches may yield different estimates of PMP. For this reason various levels of PMP may be considered, as discussed in section 1.2.

1.1.4 Probable maximum storm (PMS)

PMP for all durations and sizes of area in a specific basin is usually determined by several types of storms. For example, thunderstorms are very likely to provide PMP over an area smaller than about 1 000 km^2 for durations shorter than 6 hours, but controlling values for longer durations and larger areas will be derived almost invariably from general storms. For short durations, thunderstorms can produce heavier rainfall than can general storms, but they are relatively short-lived, and individual storms cover relatively small areas. General storms, although they often include thunderstorms, produce less intense rainfall on the average, but their longer life and greater areal coverage result in greater rainfall amounts for durations of about 6 hours and longer, and for large areas.

Normally, it would appear illogical to assume that PMP for all durations and sizes of area could be realized from one storm, but this is not necessarily so. PMP for small basins may be, and is often assumed to be, obtainable from a single storm. In such cases, PMP and PMS are synonymous, but this is not always so. PMP values for all ranges of duration and sizes of area in a basin are always understood to represent limiting rainfall amounts without regard to storm type. In other words, PMP values envelop the probable maximum amounts that might be realized from any type of storm that could produce heavy precipitation over the basin. PMS, on the other hand, may refer to any maximized observed or hypothetical storm that is equal to PMP for at least one duration and size of area. The term has been applied also to a hypothetical storm that would produce PMP for all durations at the total basin area and somewhat lesser values for smaller areas within the basin.

1.2 Lower and upper limits of PMP

1.2.1 Accuracy of PMP estimates

That the procedures described here for deriving estimates of PMP yield results to the nearest millimeter or tenth of an inch should not be taken as an indication of the degree of accuracy of the estimates. There is no objective way of assessing the general level of PMP estimates derived by the procedures described here or by any other known procedures. Judgment based on meteorology and experience is most important. Obviously, estimates subsequently exceeded by observed storm rainfall were too low. There is no way, however, that an estimate can be labelled with certainty as being too low or too high at the time it is made. Their accuracy may be assessed, however, by consideration of the following factors: (1) excess of estimated PMP over the maximum observed rainfall values for the project basin and surrounding region; (2) number and severity of record storms; (3) limitations on storm transposition in the region; (4) number, character, and interrelationship of maximizing steps; (5) reliability of any model used for relating rainfall to other meteorological variables; and (6) probability of occurrence of the individual meteorological variables used in such models, with care being taken to avoid excessive compounding of probabilities of rare events.

Subsequent chapters show that various steps in the procedures require meteorological judgment. Consequently, the resulting estimates can be conservative or liberal depending on decisions affecting the degree of maximization used in their derivation. Thus, in effect, lower and upper limits to PMP can be estimated, although only one set of values is usually derived.

1.2.2 Confidence bands

The delineation of lower and upper limits to PMP is somewhat analogous to the confidence bands used in statistical work. It would be nice if a confidence band could be placed about a PMP estimate in an objective manner, similar to the standard statistical method, but this is not possible because PMP is not estimated by formal statistical methods. This limitation, however, does not invalidate the concept of a confidence band, but it means that its limits must be based in considerable measure on judgment, as is the PMP estimate itself. Factors influencing such judgment are the same as those for assessing the general level of PMP listed in the preceding paragraph.

1.3 The manual

1.3.1 Purpose

The following statement was published in a UN/WMO report [4]: "The practice of hydrometeorology has not been reduced to a handbook. No one can furnish a set of rules, graphs, and procedures whereby one can proceed step by step and necessarily derive an acceptable estimate of probable maximum rainfall. The lectures will discuss only certain principles. Handbooks work best in solving uniform problems from data that are uniform and ample. None of these three conditions is the rule in probable maximum rainfall estimates - neither problems nor data are uniform, and the data are certainly not ample."

There is no disagreement with this statement. No two basins present exactly the same problems as they vary in size, shape, orientation and other geographic features. Also, the type, amount and quality of meteorological data available differ from basin to basin. Nevertheless, it is believed that a useful purpose would be served by some description, in as much detail as possible, of the more commonly used procedures for estimating PMP. It is for this reason that this manual has been prepared. With the procedures and examples presented here, the hydrometeorologist with some ingenuity should be able to make the necessary modifications to adapt the procedures to his particular problems.

1.3.2 Scope

The manual describes the more common meteorological approaches for estimating PMP in orographic and non-orographic regions and for regions with and without adequate meteorological data. It also describes a statistical procedure for small basins. Generalized estimates, storm transposition, and seasonal variation are discussed also. The text is restricted to methods for estimating PMP, and does not include procedures for deriving maximum seasonal snowfall accumulations, optimum melting rates, etc.

Estimation of PMP for very large basins is usually a complicated problem [2, 3]. The continued deposit for several days throughout an area of hundreds of thousands of square kilometers of precipitation at a rate computed from a sustained maximum inflow of moist air with maximum moisture content, and released by repeated development of storm mechanisms of maximum efficiency, would be many times greater than what is experienced in the situations producing the maximum floods, and would be an unreasonably excessive estimate of maximum precipitation. For this reason, the various meteorological procedures described here are considered most applicable to basins up to about 50 000 km^2, although they have been used for much larger basins.

The meteorological procedures discussed are more suited to middle latitudes than to the tropics. In the tropics the heaviest rainfalls are associated with very high atmospheric moisture, which prevails most of the time during the rainy season. Hence, there is neither theoretical nor empirical reason to relate rainfall potential to the minor fluctuations in humidity that occur. It is for this reason that the meteorological procedures presented are considered to be generally inapplicable to the derivation of PMP estimates for the tropics.

1.3.3. Use of examples from actual studies

Examples from published reports on estimates of PMP for various basin sizes in regions with different climates and topography are used in the following chapters to describe the more generally applicable procedures for making such estimates. There are two main reasons for using such examples. One is that they are real estimates made for real situations, and thus should inspire more confidence in the procedures than would descriptions of hypothetical situations. The second reason is that the published reports from which the examples were taken provide more detail than can be given in this manual, and they are available for reference. The information presented in this manual, however, should be adequate for describing procedures. While estimates of PMP have been made by various countries, the examples used are from reports published by the U.S. Weather Bureau, renamed National Weather Service in 1970. It should not be inferred that the procedures and results presented in these reports are superior to those derived by other agencies or nations. The chief reason for using examples from reports prepared by the Weather Bureau (now National Weather Service) is that it has issued published reports, particularly in its Hydrometeorological Report series, giving detailed descriptions of over four dozen PMP studies made for various parts of the world. Most, of course, are for the United States, which, because of its wide variety of climate and topography, presents a wide range of problems involved in the derivation of PMP estimates. Some reports are on studies made for specific river basins, while others present generalized estimates. Both types are discussed here.

The examples presented are not intended for direct application in deriving PMP estimates. They serve merely to show how PMP has been estimated in a number of different situations involving different basin sizes, topography, climate, and data availability. It should not be inferred that the example given for any particular situation represents the only solution. Equally valid results might have been obtained by other approaches. The examples should thus be looked upon as suggestions on how to approach derivation of PMP estimates. Particular attention should be paid to the cautionary remarks at the end of each chapter.

Although barely mentioned in the manual, the importance of meteorological studies in preparing PMP estimates cannot be over-emphasized. Such studies give guidance to regional, seasonal, durational, and areal variations and to topographic effects.

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CHAPTER 2

ESTIMATES FOR NON-OROGRAPHIC REGIONS

2.1 Introduction

2.1.1 Convergence model

The theoretical interrelationship of convergence, vertical motion and condensation is well known. If the convergence at various heights in the atmosphere or the vertical motion (averaged over some definite time and space) is known or assumed with a given degree of precision, then the other can be calculated to an equal precision from the principle of continuity of mass.

Observations confirm that the theoretical pseudo-adiabatic lapse rate of temperature of ascending saturated air from which precipitation yield is calculated is closely approximated in deep precipitating clouds. The higher the specific humidity, the greater the precipitation yield for a given decrease in pressure. All these factors are basic to the formulation of a convergence model, and several such models have been postulated [6, 10, 11].

2.1.2 Observed storm rainfall as an indicator of convergence and vertical motion

There is a problem in estimating probable maximum precipitation (PMP) with a convergence model. Maximum water vapour content can be estimated with acceptable accuracy for all seasons for most parts of the world by appropriate interpretation of climatological data. However, there is neither an empirical nor satisfactory theoretical basis for assigning maximum values to either convergence or vertical motion. Direct measurement of these values has been elusive. The solution to this dilemma has been to use observed storm rainfall as an indirect measure.

Extreme rainfalls are indicators of maximum rates of convergence and vertical motion in the atmosphere, which are referred to as the storm, or precipitation-producing, mechanism. Extreme mechanisms for extreme storms may then be determined for basins under study without the necessity of actually calculating the magnitude of the convergence and vertical motion. The procedures used for maximizing observed storm rainfall to estimate PMP involve moisture adjustments, storm transposition and envelopment, and these are discussed in the following sections.

2.2 Estimation of atmospheric moisture

2.2.1 Assumption of a saturated pseudo-adiabatic atmosphere

Since many of the extreme, or major recorded storms occurred before extensive networks of upper-air temperature and humidity soundings had been established, any index of atmospheric moisture must be obtainable from surface observations. Also, current upper-air observational networks are still too sparse to define adequately the moisture inflow into many storms, especially those limited to areas of the size considered in this report.

Fortunately, the moisture in the lower layers of the atmosphere is that most important for producing precipitation, both because most of it is in the lower layers and because it is distributed upward through the storm early during rainfall [5, 7]. Theoretical computations show that, in the case of excessive rains, ascensional rates in the storm must be so great that within an hour or so air originally near the surface has reached the top of the layer from which precipitation is falling. In the case of severe thunderstorm rainfall, surface air may reach the top in a matter of minutes.

The most realistic assumption seems to be that the air ascends dry-adiabatically to the saturation level and thence moist-adiabatically. For a given surface dew point, a column of air will contain more moisture the lower the level at which the air reaches saturation, the greatest precipitable water occurring when this level is at the ground. For these reasons, hydrometeorologists generally postulate a saturated pseudo-adiabatic atmosphere for extreme storms.

2.2.2 Surface dew points as a moisture index

Moisture maximization of a storm requires identification of two saturation adiabats. One typifies the vertical temperature distribution in the storm to be maximized, and the other is the warmest saturation adiabat to be expected at the same place and time of year as the storm. It is necessary to identify these two saturation adiabats with some indicator, and the conventional label in meteorology for saturation adiabats is the wet-bulb potential temperature, which corresponds with the dew point at 1 000 mb. Tests have shown that storm and extreme values of precipitable water may be approximated by estimates based on surface dew points when saturation and pseudo-adiabatic conditions are assumed [7].

Surface dew points representative of the moisture inflow into the storm identify the storm saturation adiabat. The moist adiabat corresponding to either the highest recorded dew point for the location and season or the dew point for some specific return period, say, 100 years, is considered sufficiently close to the probable warmest saturation adiabat. Both storm and maximum dew points are reduced pseudo-adiabatically to the 1 000 mb level (Figure 2.1) so that dew points observed at stations at different elevations are comparable. This permits construction and use of tables showing atmospheric moisture as a function of the 1 000 mb dew points (Annex 1).

2.2.3 Persisting 12-hour dew points

As the moisture has an appreciable effect on the storm, precipitation must be that which persists for hours rather than minutes. Also, any single observation of dew point may be considerably in error. There is, then, merit in basing dew-point values to be used in estimating storm and probable maximum moisture on two or more consecutive measurements separated by a reasonable time interval or a continuous automatic record of dew point over a period of time rather than on a single reading. The so-called highest persisting 12-hour dew point is generally used. This is the highest

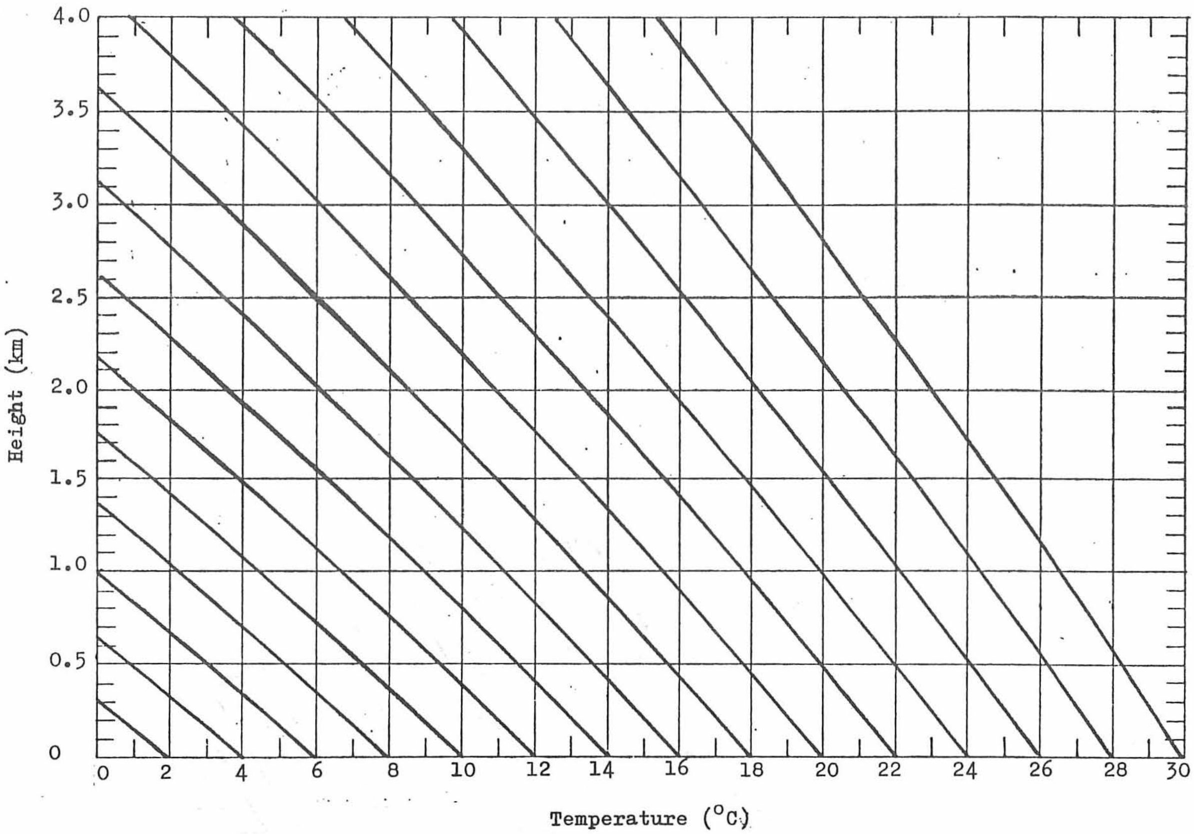

Figure 2.1 - Pseudo-adiabatic diagram for dew-point reduction to 1 000 mb at height zero

value equalled or exceeded at all observations during a 12-hour period. For example, the following is a series of dew points observed at 6-hour intervals:

Time:	00	06	12	18	00	06	12	18
Dew point (°C):	22	22	23	24	26	24	20	21

The highest persisting 12-hour dew point for this series is 24°C, which is obtained from the period 18 to 06. However, if the air temperature had dropped below 23°C during the period 00 to 06, the highest persisting 12-hour dew point would then be 23°, which is obtained from the period 12 to 00. Hourly dew points may be used, of course, but such records are sparse, and they add a great deal of work to the surveys for persisting values, especially in the case of maximum persisting 12-hour dew points, which are discussed in section 2.2.5.

2.2.4 Representative persisting 12-hour 1 000 mb storm dew points

To select the saturation adiabat representing the storm moisture, the highest dew points in the warm air flowing into the storm are identified from surface weather charts. Dew points between the rain area and moisture source should be given primary consideration. Dew points in the rain area may be too high because of the precipitation, but they need not be excluded if they appear to agree with dew points outside the area. In some storms, particularly those with frontal systems, surface dew points in the rain area may represent only a shallow layer of cold air and not the temperature and moisture distributions in the clouds releasing the precipitation.

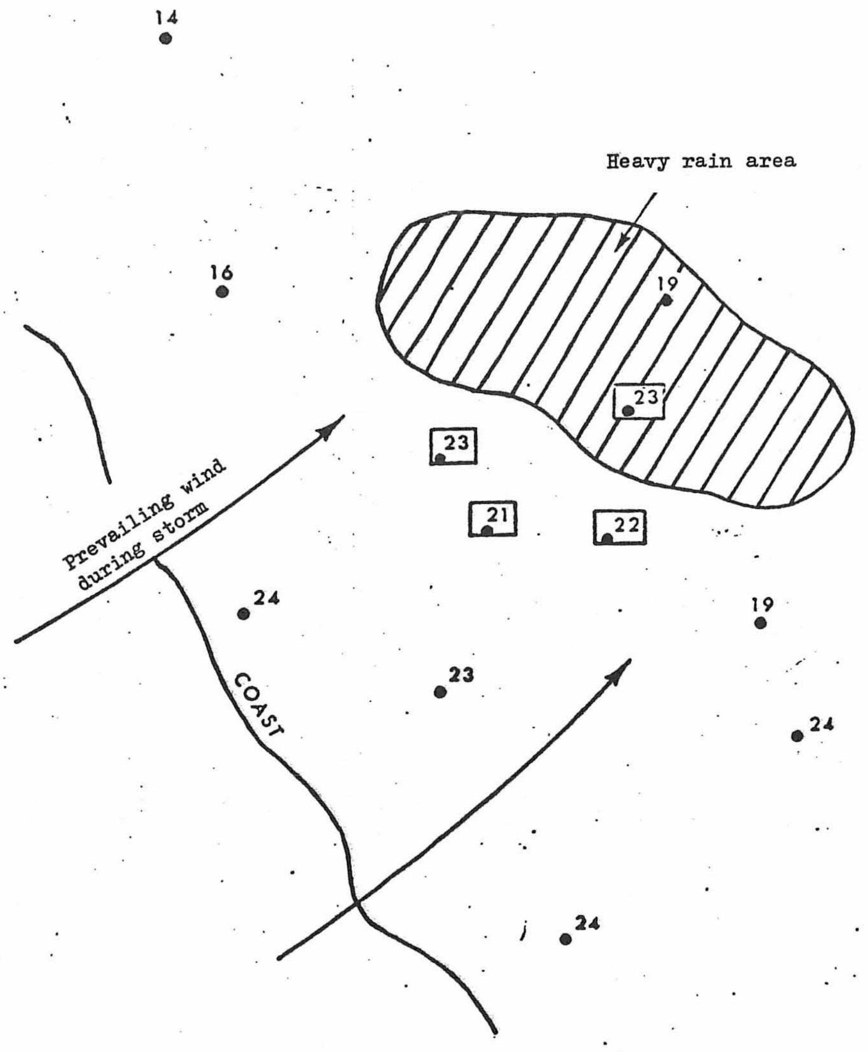

Figure 2.2 - Determination of maximum dew point in a storm. Representative dew point for this map time is average of values in boxes

Figure 2.2 illustrates schematically a weather map from which the storm dew point is determined. On each consecutive weather map, say, for 6-hour intervals during the storm, the maximum dew point is averaged over several stations, as illustrated in the figure. Occasionally, for lack of data, it is necessary to rely on the dew point at only one suitably located station. The single or average maximum dew points selected from each map form a series, and the maximum persisting 12-hour storm dew point is then selected, as described in section 2.2.3. The selected dew point is then reduced pseudo-adiabatically to the 1 000 mb level.

If the originally observed values plotted on the weather maps are for stations differing appreciably in elevation, the reduction to 1 000 mb should be made before averaging. However, elevation differences between dew-point stations in the moist-air inflow are usually small and are generally neglected in the selection of the storm dew point.

2.2.5 Maximum persisting 12-hour 1 000 mb dew points

Maximum values of atmospheric water vapour used for storm maximization are usually estimated from maximum persisting 12-hour 1 000 mb dew points. These dew points are generally obtained from surveys of long records, say 50 or more years, at several stations in the problem area. In some regions, the maximum dew points for each month of the year or critical season may be adequate to define the seasonal variation of maximum atmospheric moisture, but it is generally advisable to select maximum 12-hour dew points by semi-monthly or 10-day intervals.

Dew-point records appreciably shorter than about 50 years are unlikely to yield maximum values representative of maximum atmospheric moisture. The usual practice in such cases is to make a frequency analysis of the annual series of monthly or shorter interval maximum persisting 12-hour dew points. Since values for the 100-year return period have been found to approximate maximum dew points obtained from surveys of long records, it is the 100-year values that are generally used for defining the seasonal variation curve, although 50-year values are sometimes used.

Certain precautions are advisable in the selection of maximum dew points intended to be indices of maximum moisture for storm maximization. These precautions apply regardless of whether the maximum dew points are used directly as surveyed or subjected to frequency analysis. In certain places and seasons characterized by ample sunshine, sluggish air circulation, and numerous lakes, rivers and swamps, a local high dew point may result from local evaporation of moisture from the surface and may not be at all representative of atmospheric moisture at upper levels. Such dew points should be discarded. To eliminate dew points so affected, the surface weather charts for the dates of highest dew points should be examined and the dew points discarded if they appear to have occurred when the observing station was clearly in an anticyclonic or fair weather situation rather than in a cyclonic circulation with tendencies towards precipitation.

All values of maximum persisting 12-hour dew points selected directly from surveys of long records are plotted against date observed, and a smooth envelope drawn, as illustrated in Figure 2.3. When dew points from short records are subjected to frequency analysis, the resulting values are usually plotted against the middle

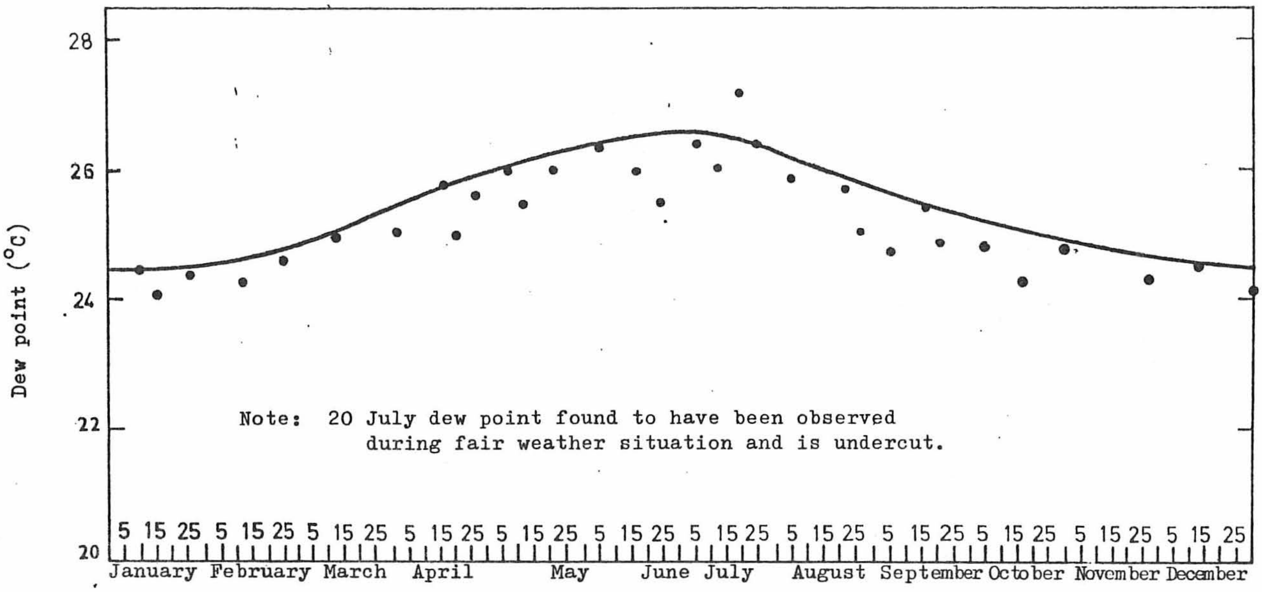

Figure 2.3 - Enveloping maximum dew points at a station

day of the interval for which the series is compiled. Thus, for example, if the frequency analysis is for the series of semi-monthly maximum persisting 12-hour dew points observed in the first half of the month, the resulting 50- or 100-year values would be plotted against the eighth day of the month.

The preparation of monthly maps of maximum persisting 12-hour 1 000 mb dew points is advisable, especially where numerous estimates of PMP are required. Such maps not only provide a ready, convenient source of maximum dew points but also aid in maintaining consistency between estimates for various basins. The maps are based on mid-month dew-point values read from the seasonal variation curves and adjusted to the 1 000 mb level. These values are plotted at the locations of the observing stations, and smooth isopleths are then drawn, as in Figure 2.4.

Some regions have no dew-point data, or a period of record so short as to preclude reliable frequency analysis. Since the chief source of moisture inflow into major storms is water evaporated from the seas or oceans, sea-surface temperatures provide a logical base for estimating maximum dew points. In fact, sea-surface temperatures may be more representative of atmospheric moisture in depth than are inland dew points, which, as mentioned earlier, may be affected by local conditions.

Estimation of maximum dew points from sea-surface temperatures is relatively simple for coastal regions since there is little modification of the moist air by passage over land surfaces. In the coastal regions of the Gulf of Mexico, for example, maximum persisting 12-hour 1 000 mb dew points range from about 1°C to 2°C below upwind, offshore mean monthly sea-surface temperatures. The difference increases with distance inland.

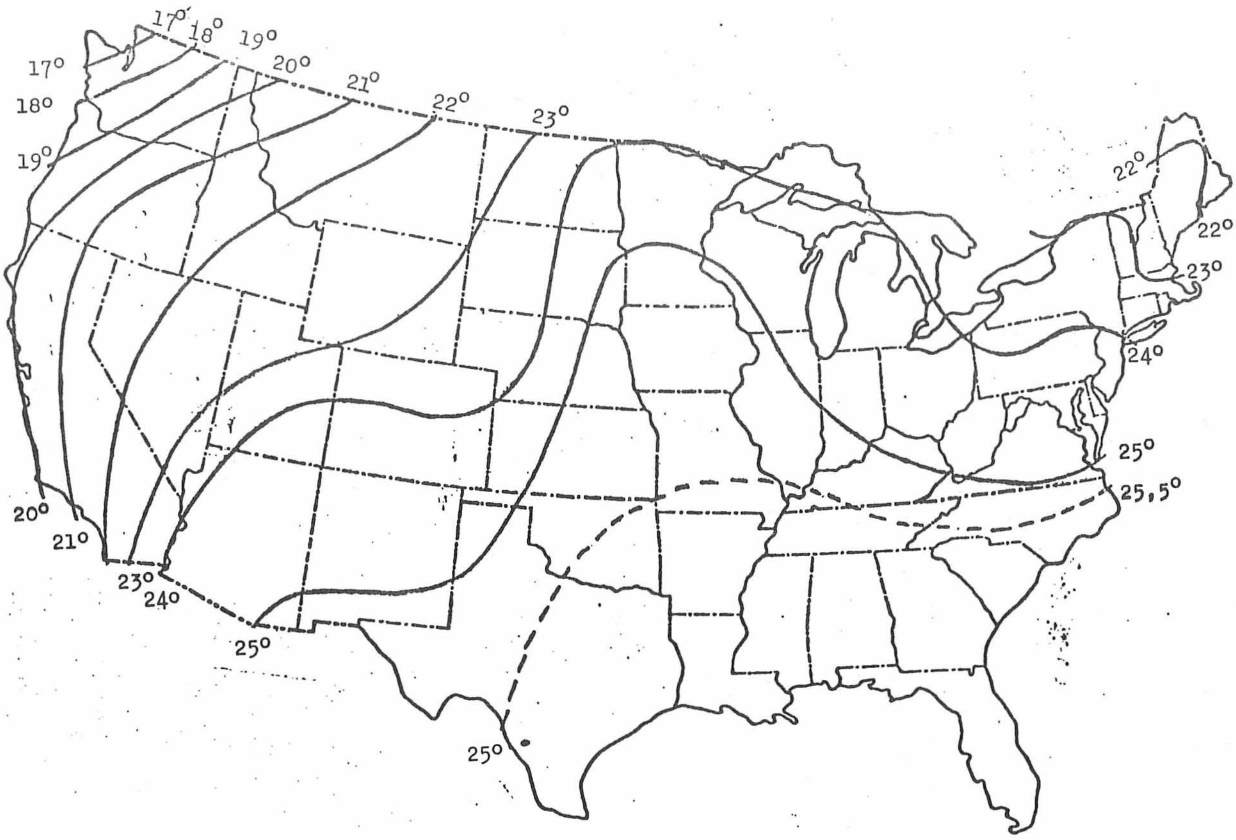

Figure 2.4 - Maximum persisting 12-hour 1 000 mb dew points for August

The rate of decrease of maximum dew points with distance inland depends upon the season of the year, direction of moisture flow during periods of maximum humidity, topographic barriers, and other geographic factors. The decrease must be determined for each month and for each region of interest in order to obtain a reasonably reliable seasonal variation curve. The gradients indicated by maps of maximum persisting 12-hour 1 000 mb dew points prepared for areas with adequate data provide the most useful guidance in determining such dew points for areas with very little or no data. The map of Figure 2.4, for example, would be useful for estimating maximum persisting dew points for regions of similar geography.

2.2.6 Precipitable water

This is a term, used mostly by hydrometeorologists, to express the total mass of water vapour in a vertical column of the atmosphere. A statement, for example, that the air contains 3 cm of precipitable water signifies that each vertical column of 1 cm^2 cross section contains 3 gm of water in vapour form. If the water vapour were all condensed into liquid water and deposited at the base of the column, the accumulated liquid would be 3 cm deep, since the density of water is 1 gm cm^{-3}. Precipitable water is, in fact, a misnomer, because no natural process will precipitate all the water vapour in the atmosphere. For this reason, the substitute terms, liquid equivalent of water vapour or, simply, liquid water equivalent, are sometimes used.

Tables of precipitable water for saturated air with a pseudo-adiabatic lapse rate between the 1 000 mb surface and various heights or pressure levels as a function of the 1 000 mb dew point are presented in Annex 1. These tables are used for moisture adjustments.

2.3 Moisture maximization

2.3.1 Seasonal limitations

Seasonal variations in storm structure place a limitation on moisture maximization. For example, a winter storm would never be adjusted for the moisture content indicated by the maximum persisting 12-hour dew point for the year if it should be in summer, which it almost always is. In practice, the moisture adjustments are made on the basis of the maximum persisting 12-hour dew point for the same time of year as the storm occurrence or, more often, the maximum persisting 12-hour dew point within 15 days. Thus, for example, if the maximum dew point for maximizing a 15 May storm was being selected from the curve of Figure 2.3, one would use the higher dew point indicated for 30 May. Similarly, the maximum dew point indicated for 15 September would be used generally for maximizing a 30 September storm.

2.3.2 Depth of precipitable water

The tables presented in Annex 1 show depth of precipitable water from the 1 000 mb surface to various altitudes or pressure levels as a function of the 1 000 mb dew point. In maximizing storm rainfall, only the depth of precipitable water from the ground to some arbitrarily selected level from 400 to 200 mb is used. The 300 mb level is accepted generally as the top of the storm, but it makes little difference which level from 400 mb on up is selected, as there is very little moisture at those heights, and the effect on the moisture adjustment is negligible. In cases where a mountain barrier lies between the storm area and the moisture source, the mean elevation of the ridge, or crest, is generally selected as the base of the moisture column. In most cases, it is advisable to select the storm and maximum dew points between the barrier and the storm location.

2.3.3 Applicability of persisting 12-hour dew points for all storm durations

The dew points from a single station or set of stations used to obtain a representative persisting 12-hour storm dew point are unlikely to be in the most intense moisture inflow for much more than 12 to 24 hours, after which the stations where the dew points were observed are very likely to be in the cold air because of the displacement of the storm. The selection of different representative 12-hour dew points for every 12 hours of a storm is a very tedious task, especially for storm durations of 72 hours and longer. Comparisons of storm rainfall values adjusted on the basis of 12-hour dew points from different sets of stations and those from a single set indicate that differences are too small to justify the additional time required for obtaining representative 12-hour dew points for different storm intervals.

It should be noted also that the use of different representative dew points for a storm requires different maximum dew points for the maximizing procedures described below. Tests of the use of representative storm dew points over time intervals up to 72 hours, e.g., 24-, 48- and 72-hour dew points, for adjusting storm rainfall values showed only small differences from the results obtained from the use of the 12-hour representative storm dew point. The general practice is to use a single representative persisting 12-hour dew point for adjusting the storm rainfall for all durations and sizes of area.

2.3.4 Maximization of storm in place

Moisture maximization of storms in place, i.e., without change in location, consists simply of multiplying the observed storm rainfall amounts by the ratio (r_m) of the maximum precipitable water (W_m) indicated for the storm location to the precipitable water (W_s) estimated for the storm, or

$$r_m = W_m/W_s \quad . \tag{2.1}$$

Thus, for example, if the representative persisting 12-hour 1 000 mb storm dew point is 21°C and the maximum is 24°C and the rain area is at an elevation of 400 m above mean sea level (always assumed to be at 1 000 mb) with no intervening topographic barrier between the rain area and moisture source, the moisture maximizing ratio (r_m) is computed from precipitable water values obtained from the tables in Annex 1: $W_m = 74 - 8 = 66$; $W_s = 57 - 7 = 50$; and $r_m = 1.32$. The precipitable water values used in determining W_m and W_s are for a moisture column with base at 1 000 mb and top at 300 mb minus the precipitable water in a column with base at 1 000 mb and top at the elevation of the rain area, i.e., 400 m.

If it is now assumed that there is an extensive, relatively unbroken range of hills with a mean crest elevation of 1 200 m, m.s.l., between the rain area and moisture source, r_m would then be determined as follows: $W_m = 74 - 23 = 51$; $W_s = 57 - 19 = 38$; and $r_m = 1.34$. Here, the precipitable water in the 1 000 to 300 mb column is decreased by that in a column with a base at 1 000 mb and top at 1 200 m, i.e., the elevation of the barrier crest and not that of the rain area. Whenever possible, however, representative storm dew points on the lee side of the barrier should be used. This is especially advisable in the case of local storms, which do not necessarily require a strong, widespread moisture inflow but may utilize moisture that may have seeped into and accumulated in the storm area during an interval of several days or longer of sluggish circulation prior to the storm.

Moisture maximization in transposing storms is somewhat more complicated and is discussed in section 2.5.

2.4 Wind maximization

2.4.1 Introduction

Wind maximization is most commonly used in orographic regions when it appears that observed storm rainfall over a mountain range may vary in proportion to the speed of the moisture-bearing wind blowing against the range. Wind maximization in such regions is discussed in sections 3.3.1.1 and 3.3.1.2. In non-orographic regions, wind maximization is used only infrequently; storms can be transposed hundreds of kilometres to synthesize an adequate storm history for a project basin. It is reasoned that moisture inflow rates recorded in extreme storms are at a maximum or near-maximum for precipitation-producing effectiveness, and there is generally no need to maximize wind speeds.

This reasoning appears logical since storms with the highest wind speeds do not necessarily produce the most intense precipitation. While it is true that hurricanes, or typhoons, with their high wind speeds tend to produce heavier rainfall amounts than do the most vigorous extratropical storms, it should be noted that their moisture content is much higher. Also, whether hurricanes with the highest wind speeds produce more rainfall than weaker hurricanes is uncertain, since they generally reach full strength over seas. It is known, however, that rainfall from hurricanes over land is not proportional to their wind speeds.

2.4.2 Use in non-orographic regions

Wind maximization is sometimes used in non-orographic regions when moisture adjustments alone appear to yield inadequate or unrealistic results. In regions with limited hydrometeorological data, for example, wind maximization may be used to compensate partly for the short period of record. The reasoning here is that the limited data available are unlikely to include extreme values of dew points or outstanding storms equivalent to those that would be observed over a long period of record. The heaviest storms recorded may be relatively weak, and their moisture inflow rates are likely to be less than those associated with maximum precipitation-producing effectiveness. Increasing both wind and moisture yields a higher degree of maximization than would moisture adjustment alone, and this compensates, in part at least, for an inadequate sample of observed data.

Wind maximization is sometimes used also when the seasonal variation of maximum 12-hour dew points gives a false indication of the seasonal variation of PMP. This is most likely to occur in regions where summers are dry and all major storms are experienced in the cold half of the year. The dew-point curve almost always peaks in summer, and the seasonal variation of maximum wind speeds must be considered in developing a representative seasonal variation curve of PMP (sections 2.10.3 and 2.10.4). In cases where this is done, individual storms are maximized for both moisture and wind, as described in sections 2.4.3, 2.4.4 and 2.9.2.

2.4.3 Winds representative of moisture inflow in storms

Low-level winds are generally used to estimate moisture inflow in storms because most of the moisture usually enters the storm system in the lowest 1 500 metres. The winds in this bottom layer can be obtained from pilot-balloon or rawinsonde observations, the winds at 1 000 and 1 500 metres perhaps being the most representative of moisture inflow. Upper-air observations, however, have relatively short records and cannot be used for maximizing the older storms. Also, pilot-balloon observations cannot be made in storms. Another shortcoming of upper-air wind observations is that they are made at considerably fewer stations than are surface-wind observations and are often inadequate for determining moisture inflow into small-area storms. For these reasons, surface data are generally used as an index of wind movement in the critical moisture-bearing layer.

2.4.3.1 Wind direction

The first consideration in developing wind adjustments is the wind direction associated with moisture inflow during major storms. Only winds from critical directions are considered in deriving wind-adjustments ratios. If more than one direction provides moist-air inflow, separate seasonal maximum wind-speed curves should be constructed for each direction. This is particularly advisable if the different wind directions bring in moisture from different source regions.

2.4.3.2 Wind speed

Various measures of wind speed have been used to develop wind maximization ratios. Among them are: (1) average wind speed through the moisture-bearing layer computed from representative soundings; (2) average speed in the moist layer computed from two or three consecutive 6- or 12-hourly soundings; and (3) average speed or total wind movement for a 12- or 24-hour period at a representative station, the 24-hour period being preferred because of diurnal variations. Only wind speeds from critical directions are considered (paragraph 2.4.3.1). Wind observations during the 24-hour period of maximum rainfall are usually the most representative of moisture inflow to storms of that or longer duration. For storms of shorter duration, average winds need be computed for the actual duration only.

2.4.4 Wind maximization ratio

The wind maximization ratio is simply the ratio of the maximum average wind speed for some specific duration and critical direction obtained from a long record of observations, say 50 years, to the observed maximum average wind speed for the same duration and direction in the storm being maximized. The monthly maximum average values obtained from the records are usually plotted against date of observation, and a smooth seasonal curve drawn so that storms for any time of the year may be maximized readily (Figure 2.12, part C). The maximum wind speeds used for maximization are read from the seasonal curve.

Wind records appreciably shorter than about 50 years are unlikely to yield maximum speeds reasonably representative of those to be obtained from a long record. Frequency analysis is advisable for such short records. The computed 50- or 100-year values, usually the former, are used to construct the seasonal variation curve of limiting wind speed.

Sometimes the moisture values (precipitable water), both maximum and storm-observed, are multiplied by the corresponding wind speeds to provide a moisture-inflow index. The advantage in this is that the resulting moisture-inflow index curve presents a more readily visualized seasonal variation of PMP (Figure 2.12, part D) than when moisture and wind-speed curves are examined separately. Also, when the seasonal variation curves are expressed in terms of percentage of the peak or other value, the moisture-inflow index curve provides a single percentage value for adjusting PMP values for any particular time of year.

2.5 Storm transposition

2.5.1 Definitions

The outstanding rainstorms in a region surrounding a project basin are a very important part of the historical evidence on which a PMP estimate for the basin is based. The transfer of storms from locations where they occurred to other areas where they could occur is called storm transposition.

Transposition limits refer to the outer boundaries of a region throughout which a storm may be transposed with only relatively minor modifications of its rainfall amounts. The area within the transposition limits has similar, but not identical, climatic and topographic characteristics throughout. More restricted transposition limits may be defined if a region has a long record of precipitation measurements from a relatively dense network of gauges and has experienced several outstanding storms. Where the record of storms is more limited, either because of a sparse raingauge network or because of very infrequent occurrence of severe storms during the period of record, then more liberal, though perhaps less reliable, transposition limits must be accepted.

A transposition adjustment is a ratio by which the storm rainfall amounts are multiplied to compensate for differences between conditions at the storm site and those at the project basin.

2.5.2 Steps in transposition

The transposition procedure involves the meteorological analysis of the storm to be transposed, the determination of the limits of transposability, and the application of the proper adjustments for making the modifications required by the change in storm location. The procedure may be divided into four steps, as in the following paragraphs.

2.5.2.1 The storm

The first step in transposing a storm is to identify clearly when and where the heaviest rainfall occurred and the approximate causes in terms of synoptic meteorology. An isohyetal chart, a few key mass rainfall curves, and weather maps serve these purposes. The isohyetal chart may be a simple one, since its primary function is to identify the storm location. Routinely available weather maps may be sufficient to identify the storm causes, especially if the precipitation is closely associated with either a tropical or an extratropical cyclone. In other instances, a detailed analysis may be necessary to identify causes.

2.5.2.2 Region of influence of storm type

The second step is to delineate the region in which the meteorological storm type identified in step 1 is both common and important as a producer of precipitation. This is done by surveying a long series of daily weather charts. Tracks of tropical and extratropical cyclones are generally available in published form, and these may be used to delineate the regions frequented by the various storm types.

2.5.2.3 Topographic controls

The third step is to delineate topographic limitations on transposability. Coastal storms are transposed along the coast, but only a limited distance inland. Transposition of inland storms is restricted to areas where major mountain barriers do not block the inflow of moisture from the sea unless such blocking prevailed at the original storm site. Adjustments for transposition behind moderate and small barriers are discussed in section 2.6.3. Some limitation is placed on latitudinal transposition in order not to involve excessive differences in air mass characteristics. Figure 2.5 shows the transposition limits for a summer storm in Kansas, U.S.A. In estimating PMP over a specific basin, it is only necessary to determine if a particular storm can be transposed to the problem basin, and delineation of the entire area of transposability is not required. It is required, however, in the preparation of generalized estimates, which are discussed in Chapter 5.

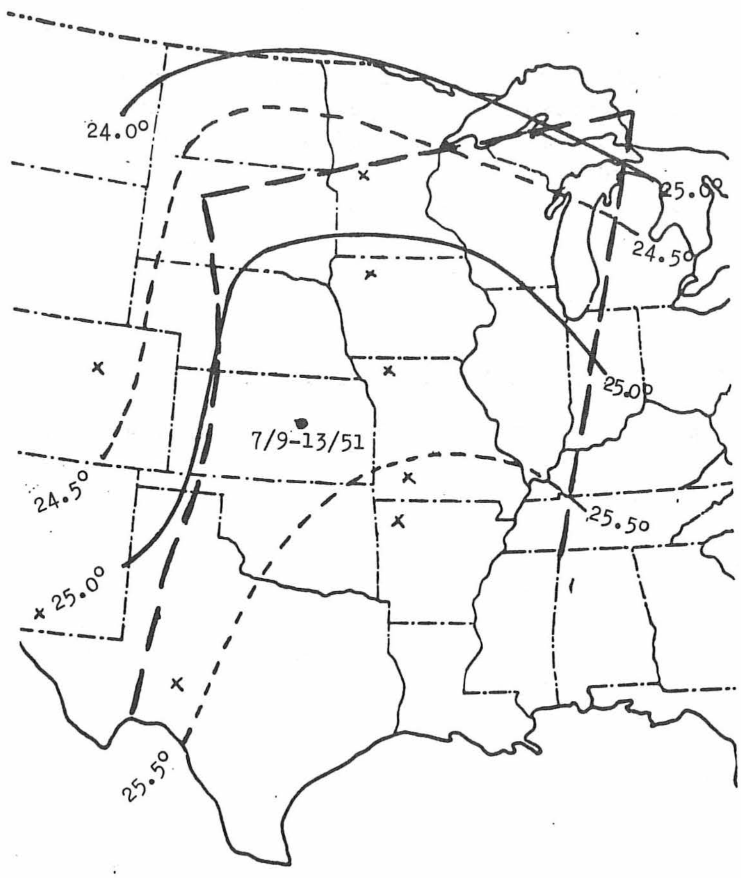

Figure 2.5 - Transposition limits (heavy dashed line) of 9-13 July, 1951 storm. Locations of synoptically similar summer storms marked X. Light lines indicate maximum persisting 12-hour 1 000 mb dew points (°C) for July.

2.5.2.4 Adjustments

The final step in transposition is the application of adjustments discussed in the following section.

2.6 Transposition adjustments

2.6.1 Moisture adjustment for relocation

Simply stated, the moisture adjustment is merely the multiplication of the observed storm rainfall amounts by the ratio of the precipitable water (W_2) for the enveloping, or maximum, dew point at the transposed location to that, W_1, for the representative storm dew point, or

$$R_2 = R_1 (W_2/W_1) \tag{2.2}$$

where R_1 is the observed storm rainfall for a particular duration and size of area, and R_2 is the storm rainfall adjusted for transposition. Equation 2.2 incorporates both a transposition adjustment and a moisture maximization. The storm depth-area-duration array of rainfall values, such as in Table 2.1, is multiplied by this ratio. There is, of course, no need to adjust values for areas exceeding the basin size. The moisture adjustment may be either greater or less than unity, depending on whether the transposition is toward or away from the moisture source and whether the elevation of the transposed location is lower or higher than that of the original storm site.

2.6.1.1 Reference dew point for moisture adjustment

For reasons given in section 2.2.4, dew points between the rain area and moisture source tend to be more representative of the atmospheric moisture content, or precipitable water, flowing into the storm than dew points within the rain area. Such representative dew points may be a few hundred kilometres away from the storm centre. In maximizing for moisture, the maximum dew point used is for the same location as that of the representative storm dew point. In transposing, the same reference distance is laid out on the same bearing from the transposition point, as shown in Figure 2.6. The referenced dew-point location is then used for obtaining the maximum dew point from the maximum dew-point chart for calculating the maximization and transposition adjustments.

2.6.2 Elevation adjustments

An increase in surface elevation decreases the moisture that may be contained in a column of the atmosphere. However, many storms receive most of their moisture in a strong low-level flow 1 to 1.5 km deep, and this inflow is not necessarily affected appreciably by relatively small changes in ground elevation. Ranges of low hills or gradually rising terrain may actually stimulate convection and increase rainfall. This effect on precipitation may more than compensate for the decrease in precipitable water with increasing ground elevation. Elevation adjustments for PMP estimates for non-orographic regions in the middle latitudes are discussed in the next two paragraphs.

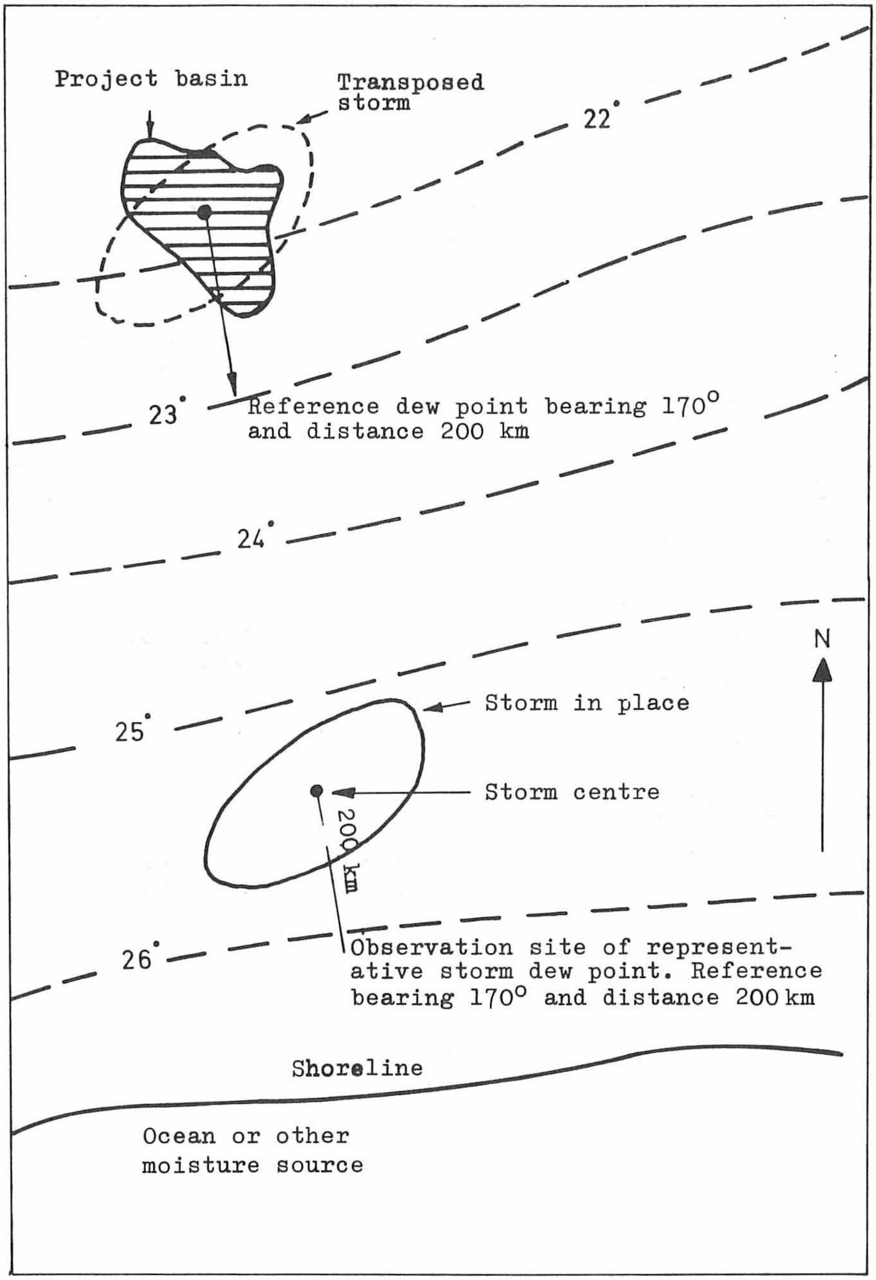

Figure 2.6 - Example of storm transposition. Long dashed lines indicate maximum persisting 12-hour 1 000 mb dew points (°C) for the same time of year the storm occurred or within 15 days according to common practice (paragraph 2.3.1)

2.6.2.1 General storms

Because of uncertainty as to the effects of relatively small or gradual elevation changes on precipitation, there are differences of opinion as to whether or not elevation adjustments should be made for storm transposition over broad, gradually sloping plains. Decision as to the use or non-use of an elevation adjustment is based on comparisons of major storms in the vicinity of the actual site of the storm to be transposed with those in the area surrounding the project site. For example, if observed major storms for the two sites showed differences in magnitude ascribable only to differences in moisture, not involving elevation differences, omission of an elevation adjustment would be justified. If it is decided to omit adjustment for elevation, W_2 of equation (2.2) is computed for the maximum dew point at the referenced location (paragraph 2.6.1.1) for the project site and the same column height as for W_1. If an adjustment is used, W_2 is computed for the same maximum dew point just described but for the column above the ground at the project site, which may be lower or higher than the site of the observed storm. Regardless of whether or not an elevation adjustment is used, transposition involving elevation differences of more than 700 m is generally avoided.

2.6.2.2 Local thunderstorms

Intense local thunderstorms are not adjusted for elevation when transposition involves elevation differences of less than about 1 500 m. Since this chapter deals with non-orographic regions, it can be stated, simply, that no elevation adjustment is made for local thunderstorms. Elevation adjustment for such storms is required in orographic regions, however, and they are discussed in sections 5.3.3.1 and 5.3.6.4.

2.6.3 Barrier adjustment

Transposition of a storm from the windward to the leeward side of a topographic barrier normally requires an adjustment for the height of the barrier. This is a common situation, because basins upstream from a proposed dam site are often rimmed by mountains or hills. Transposition of storms across barriers higher than about 700 m above the elevation of the observed storm site is generally avoided because of their dynamic influence on storms. Also, barrier adjustments are not used in transposing local, short duration, intense thunderstorms, which can draw in moisture entrapped by the barriers prior to the storm. The example of storm transposition presented in the next section includes a barrier adjustment.

2.6.4 Example of storm transposition and maximization

2.6.4.1 Hypothetical situation

Assume that synoptic weather charts associated with major storms indicate that the hypothetical storm pattern shown in Figure 2.6 is transposable to the project basin shown in the same illustration. The average elevation of the storm area is 300 m, and that of the moisture-inflow, or south, side of the basin is 700 m, with no intervening orographic barriers. The representative persisting 12-hour storm dew point (section 2.2.4) is 23°C, which was observed at a site (Figure 2.6) located at an elevation of 200 m and 200 km from the storm centre on a bearing of 170° (paragraph 2.6.1.1). Reduction of this dew point to the 1 000 mb level (Figure 2.1) yields 24°C.

2.6.4.2 Computation of adjustment factor

The adjustment factor, or ratio, is computed as follows:

$$r = (W_{26}/W_{24})_{300} \times (W_{23}/W_{26})_{300} \times (W_{23})_{700}/(W_{23})_{300} =$$

$$(W_{23})_{700}/(W_{24})_{300} \qquad (2.3)$$

where the subscripts within parentheses refer to the 1 000 mb dew points for which the precipitable water W is computed, and the subscripts outside parentheses refer to the various pertinent ground elevations forming the bases of the atmospheric columns for which W is computed. Thus, the term $(W_{26}/W_{24})_{300}$ represents moisture maximization at the storm site; $(W_{23}/W_{26})_{300}$ is the adjustment for the difference in maximum dew points of the original and transposition locations; and $(W_{23})_{700}/(W_{23})_{300}$ is the elevation adjustment. Multiplication of all these terms leads to a simple result that all the required adjustments are implicit in the single term $(W_{23})_{700}/(W_{24})_{300}$. Referring to Tables A.1.1 and A.1.2 for a column top of 300 mb, $(W_{23})_{700}$ = 67 - 13 = 54, and $(W_{24})_{300}$ = 74 - 6 = 68mm. Hence, r = 54/68 = 0.79.

Table 2.1 - Maximum average depth (mm) of rainfall in storm of 20-23 May 1927

Area (km^2)	Duration (hours)							
	6	12	18	24	36	48	60	72
25*	163	208	284	307	318	328	343	356
100	152	196	263	282	306	324	340	353
200	147	190	251	269	300	321	338	352
500	139	180	234	250	290	315	336	351
1 000	133	171	220	235	278	304	328	341
2 000	124	160	202	215	259	284	308	322
5 000	107	140	172	184	218	241	258	274
10 000	91	118	140	151	182	201	215	228
20 000	66	87	104	114	143	158	173	181

*Assigned area for maximum station precipitation.

If an extensive orographic barrier (section 2.6.3) of, say, 1 000 metres in mean elevation lay between the observed storm site and the project basin, (W_{23}) 1 000 would be substituted for $(W_{23})_{700}$, and ration r would then be (67 - 18)/(74 - 6), or 0.72. The appropriate rations then applied to the storm depth-area-duration data like those of Table 2.1. Other storms are adjusted similarly by appropriate ratios, and the results are then treated as described in sections 2.8 and 2.9.

2.7 Sequential and spatial maximization

2.7.1 Definition

Sequential and spatial maximization involves the development of hypothetical flood-producing storms by combining individual storms or rainfall bursts in individual or separate storms. The combination is effected by hypothesizing critical sequences with minimum time intervals between individual events (sequential maximization), which also may be repositioned, or transposed, geographically (spatial maximization).

2.7.2 Sequential maximization

Sequential maximization is the rearrangement of observed storms or portions thereof into a hypothetical sequence such that the time interval between storms is at a minimum. The storms may have occurred in close succession, or they may have occurred years apart. The procedure is most often used for large basins, where outstanding floods result from a sequence of storms rather than from a single event. For small basins, where rainfall for one day or less may produce the maximum flood, sequential maximization may involve the elimination or reduction of the time interval between successive bursts in the same storm or in separate storms.

The initial step for sequential maximization is the same for large or small basins. In each instance, a thorough study of the meteorology of major storms in the area of interest is required [1, 8, 9]. Storm types associated with heavy rainfalls in or near the project basin are determined. Movements of surface and upper-air lows and highs are examined; depth, breadth, and direction of moisture inflow are determined; vorticity advection is investigated; etc. It is usually impossible to study all major storms with the same degree of detail. In the case of older storms, for example, upper-flow patterns must be estimated from surface data.

The next step is to determine the sequences of storms in and near the project basin. For large basins, storm sequences should be examined to determine the shortest reasonable time interval between individual storms of various types. The minimum time interval, usually measured in days, should be determined for each combination of storm types producing heavy precipitation. This interval is a critical factor in the hypothetical storm sequence established. For small basins, the procedure, though similar, concentrates on the interval, usually measured in hours, between bursts in individual storms. In some instances, the combination of bursts from separate storms is a possibility, and the time interval between similar storms should be considered.

After storms have been examined and reasonable minimum time intervals between them determined, pairs or sequences of storms or bursts are developed. Each pair of storms, or for small basins individual bursts within a storm, is examined carefully to insure that meteorological developments following the first storm or burst, i.e., movement of lows and highs, over-running of the basin by cold air, etc., would not prevent the succeeding storm or burst from occurring within critical time limits.

If all the important features of the weather situation at the beginning of the second storm can be developed in a logical manner over a sufficiently large area, the necessary conditions for its onset will have been met. The successive hypothetical synoptic weather maps for the interval between storms or bursts are patterned to the greatest extent possible after the actual maps following the first storm or burst and preceding the second. Synoptic features, such as highs, lows, and fronts, are allowed to move and change, as indicated by experience, at a somewhat faster than average, but not excessive, rate. The resulting hypothetical storm sequence is intended to depict a critical, meteorologically possible transition from one storm or burst to another.

While the derived hypothetical storm sequence often consists of two unadjusted observed storms, the probable maximum storm (PMS) is sometimes selected as the second storm of the sequence. In other words, the second storm has been maximized for moisture and perhaps wind so that it equals PMP for at least one duration and size of area (sections 1.1.4, 2.11.2 and 2.11.3). Sequences of two probable maximum storms are never developed, however, for two reasons. One is that a properly derived PMS has a very low probability of occurrence, and the probability of two such storms occurring in unusually close succession is extremely remote. The second reason is that the first PMS would be followed by a meteorological situation unfavourable for the rapid development of the second, and the longer transition period between the two would very likely make the sequence less critical hydrologically than a sequence of lesser storms with a shorter time interval between them.

2.7.3 Spatial maximization

Spatial maximization involves the transposition of storms that occurred in or near a project basin to one or more critical locations in the basin so as to obtain maximum runoff. The procedure consists of determining if particular storms can be transposed to critical locations within specified time intervals and combined to produce maximum runoff rates or volumes. Again, as in sequential maximization, the requirement is a thorough knowledge of the storms causing heavy precipitation.

The following example of spatial maximization is based on a series of heavy, localized rainfall bursts in eastern Colorado, U.S.A., during the period 14-18 June, 1965. During this period, a persistent large-scale circulation maintained a pronounced inflow of moist unstable air into the storm area. Fronts and related synoptic features played a minimal role as did high-level factors, such as vorticity advection /5/.

Two distinct, severe six-hour bursts occurred on successive days, 16 and 17 June. Isohyetal maps for the two bursts are shown in Figure 2.7. The burst on the sixteenth was centred over Plum Creek Basin (1 100 km^2) while that on the seventeenth was centred about 40 km SE. It is reasonable to assume that the rainfall centres could have occurred over the same location since the weather situation was very much the same on both days. Combination of the two isohyetal patterns on the basis of this assumption resulted in the pattern of Figure 2.8. In combining the patterns,

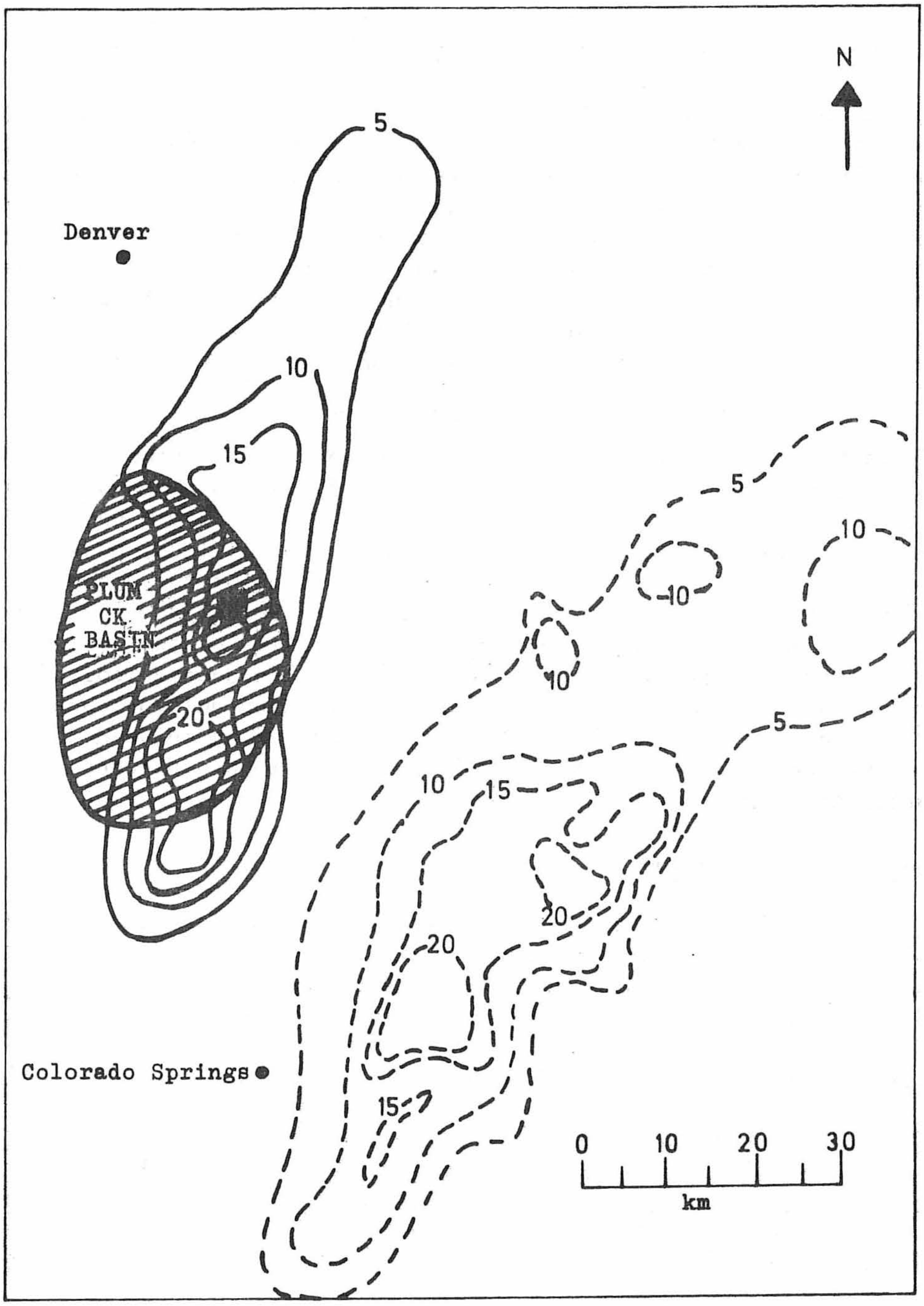

Figure 2.7 - Isohyets (cm) for the 6-hour afternoon storms of 16 June 1965 (solid lines) and 17 June 1965 (dashed lines) in eastern Colorado, U.S.A.

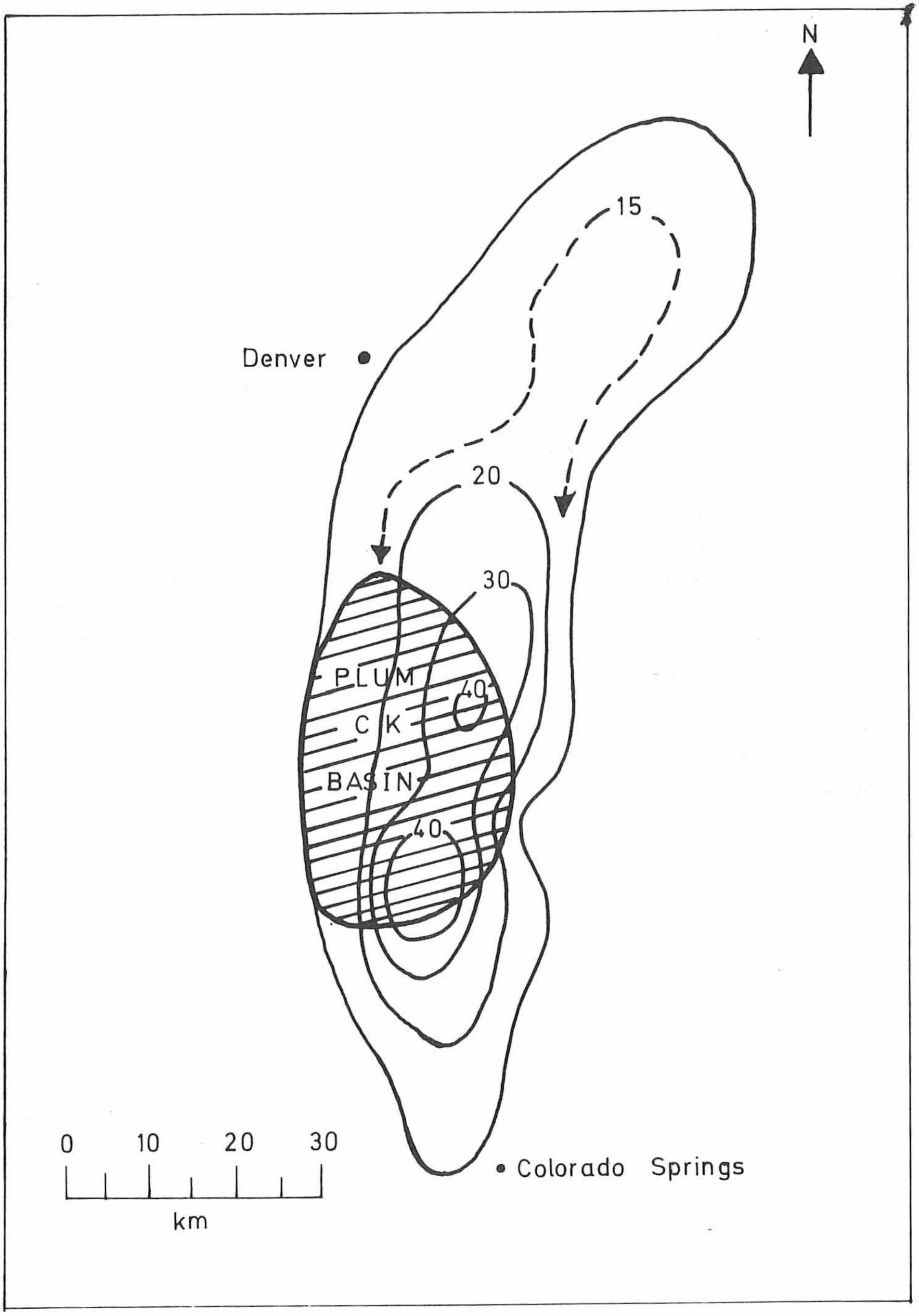

Figure 2.8 - Isohyets (cm) resulting from combination of the patterns of the 6-hour storms of 16 and 17 June 1965 shown in Figure 2.7

the principal centre of that on the seventeenth was superimposed on that of the sixteenth, and the pattern was rotated about 25 degrees counter-clockwise for better agreement with the orientation of the pattern on the sixteenth. In this region, such a rotation is realistic for this type of storm. In other regions and for other storm types, examination of many storms might show that such rotation would not be permissible.

2.7.4 Combined sequential and spatial maximization

Sequential and spatial maximizations are generally used in combination, i.e., storms or bursts within storms may be repositioned geographically in addition to shortening the time interval between them. In the study [3] from which the example of section 2.7.3 was taken, the two rainfall bursts were not only maximized spatially by superimposing centres and rotating one of the isohyetal patterns, but also the time interval between them was shortened.

The actual times of the bursts depicted in Figure 2.7 were 1 p.m. to 7 p.m., 16 June, and 2 p.m. to 8 p.m., 17 June. Examination of a large number of similar storms occurring in relatively close succession indicated that the interval between the two bursts could be reduced to 12 hours. This shortening of the time interval resulted in assigning an overall duration of 24 hours to the total rainfall for the two bursts, or seven hours less than the observed total storm period of 31 hours.

Examples of the use of sequential and spatial maximization in deriving hypothetical maximum flood-producing storm sequences for large basins may be found in references 2 and 4.

2.8 Envelopment

2.8.1 Introduction

To maximize a single storm and transpose it to a basin is a demonstration that a certain precipitation volume could fall over that basin. Nothing about the relation of this precipitation volume to PMP is revealed, and it could be far less than PMP magnitude. To consider only two or three storms or storm sequences, no matter how sophisticated the maximization and transposition adjustments might be, gives no assurance that the PMP level has been obtained.

The question of adequacy of storm sample for estimating PMP is a difficult one, especially with limited data. It seems logical, however, to expect that an envelope of rainfall values maximized and transposed to a basin is very likely to yield values indicative of PMP magnitude. This is especially true since no single storm is likely to yield extreme rainfall values for all durations and sizes of area. It is for these reasons that envelopment is considered a necessary final step in estimating PMP.

2.8.2 Envelopment

Envelopment is a process for selecting the largest value from any set of data. In estimating PMP the maximized and transposed rainfall data are plotted on graph paper, and a smooth curve is drawn through the largest values. Figure 2.9 shows an envelope of transposed, maximized precipitation values for durations up to 72 hours over a 2 000 km^2 area. The variables are changed in Figure 2.10, which is an envelope of transposed, maximized 24-hour rainfall values for areas ranging up to 100 000 km^2. In developing a full array of PMP depth-area-duration data for a basin, it is necessary to envelope both ways, as in Figures 2.9 and 2.10. Values read from the envloping curves, such as shown in these two figures, are then used to construct a set of depth-area-duration curves, as shown in Figure 2.11.

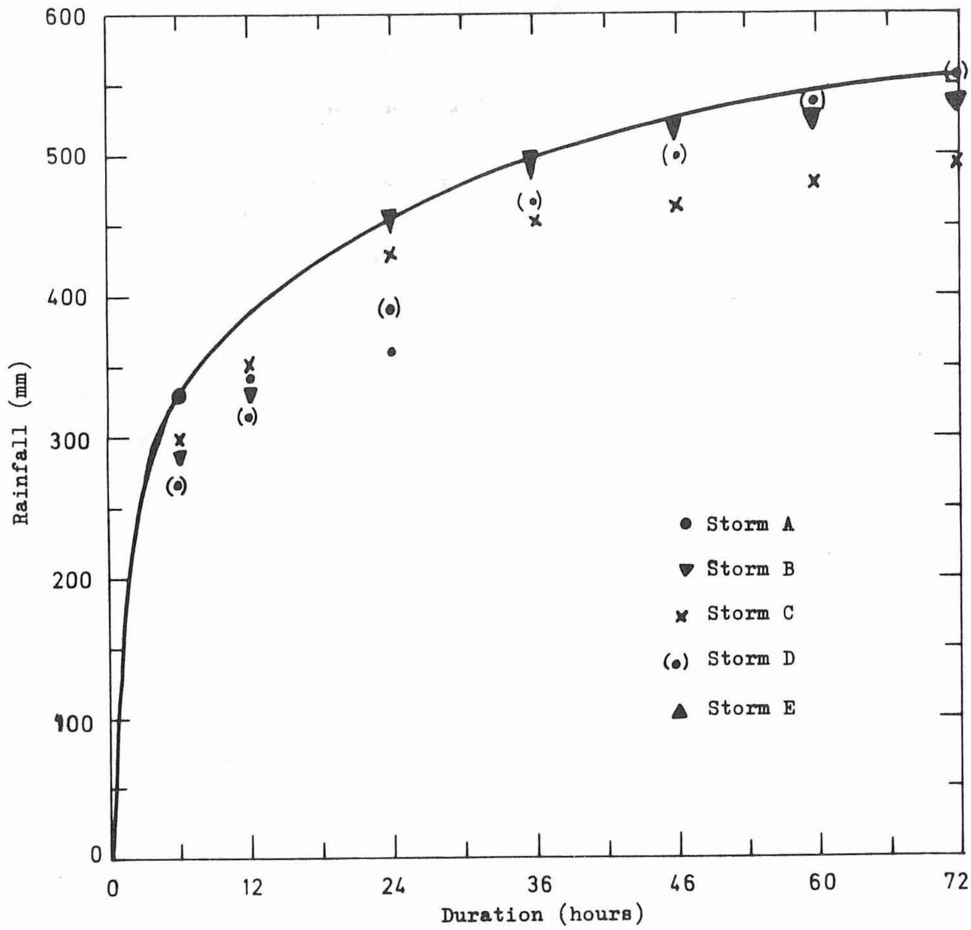

Figure 2.9 - Depth-duration envelope of transposed maximized storm values for 2 000 km^2

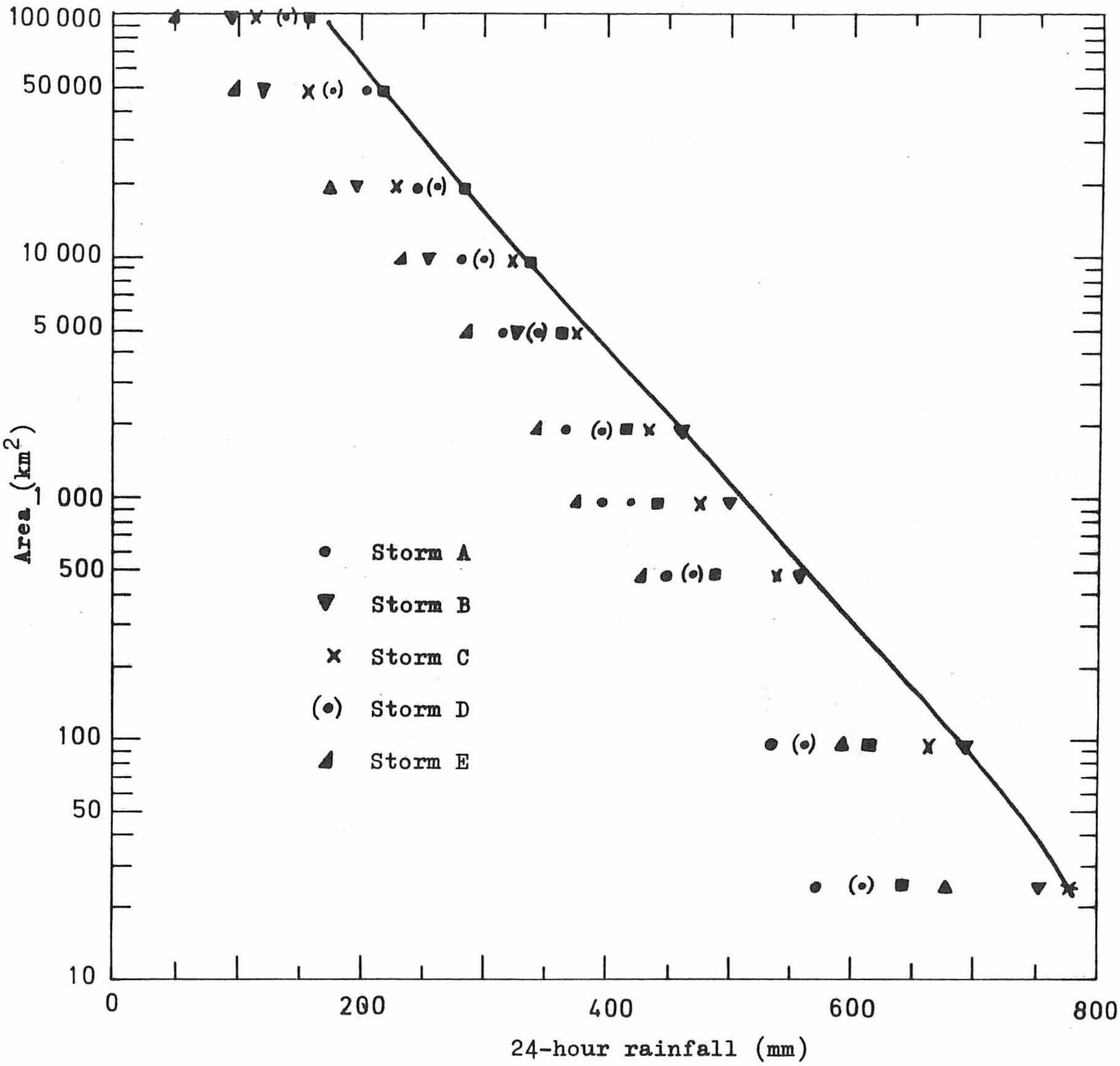

Figure 2.10 - Depth-area envelope of transposed maximized 24-hour storm rainfall values

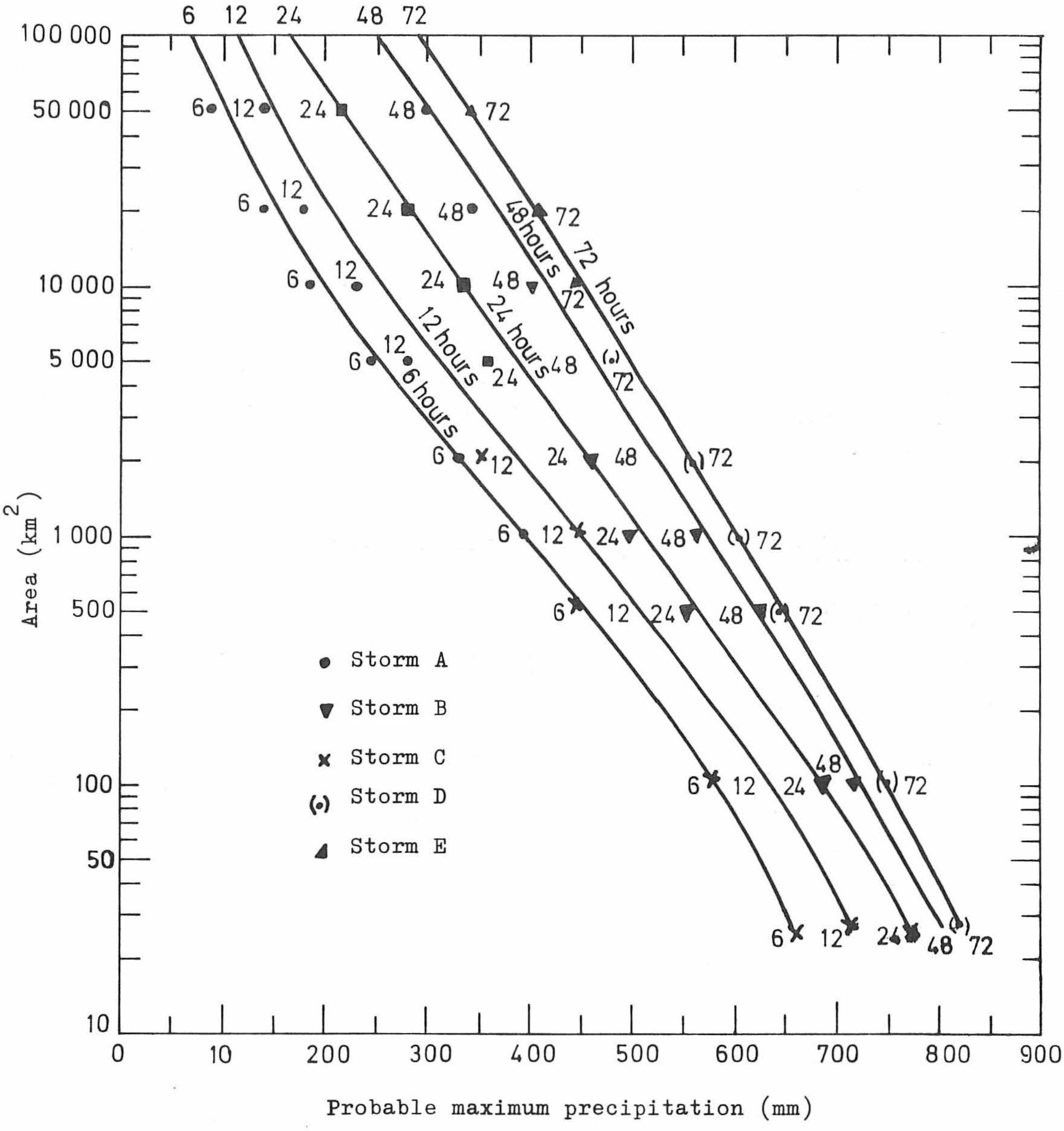

Figure 2.11 - Enveloping-depth-area-duration curves of probable maximum precipitation for a hypothetical basin

It should be noted that the controlling points determining each curve are usually from different storms. On Figure 2.11, for example, with the exception of the 6- and 12-hour curves, the points controlling the curves at about 2 500 km^2 are typically from different storms than those at 100 000 km^2. Similarly, the points controlling the short-duration curves are usually from different storms than those controlling the long-duration curves.

2.8.3 Undercutting

The data used in constructing an envelope curve are not of equal accuracy of reliability. For example, with reference to charts like those of Figures 2.9 and 2.10, the basin under study may lie definitely within the transposition limits of some of the transposed storms, but it may lie just within the fringes of the transposition limits of other storms, which leads to an element of doubt as to their transposability to this particular basin. Under these circumstances, it may be justified to place the curve at somewhat lower values than the extremes in the dubious category. This is called undercutting.

2.9 Summary outline of procedure for estimating PMP

2.9.1 Introduction

The steps outlined below for estimating PMP over a project basin are applicable only for a non-orographic region with hydrometeorological data. For most reliable estimates, data should include: (1) relatively detailed 6-hourly or daily weather maps; (2) long records, say, 50 years or more, of hourly and daily rainfall data from precipitation networks of sufficient density to permit reliable determination of time and spatial distribution of storm rainfall; (3) long records of temperature, dew-point and wind data both at the surface and, if possible, aloft, although upper-air data are not absolutely required for the procedure outlined here. It should be kept in mind that the procedure described generally applies only to middle-latitude basins of no more than about 50 000 km^2. Also, since it is very unlikely that a project basin will have experienced all the outstanding storms of the region in which it lies, storm transposition is almost always required.

2.9.2 Procedural steps

Step 1. Using weather, topographic, and preliminary total-storm isohyetal maps, determine the transposition limits of storms, as described in section 2.5.

Step 2. Survey precipitation records to obtain outstanding storms of record within the region of transposability.

Step 3. Make depth-area-duration (DAD) analyses of the storms selected in step 2, as described in "Manual for depth-area-duration analysis of storm precipitation", WMO-No. 237. TP. 129. The results of the analysis for each storm are tabulated as shown in Table 2.1. (The DAD analysis of storm precipitation is a lengthy and tedious process even when done by computer. A ready file of storm DAD data is a real convenience in making PMP estimates, and some countries maintain a continuing program of DAD analysis for accumulating a file of such data both for old storms of record and for new storms as they occur. DAD data for storms in the area of transposability may be selected readily from such files, thus eliminating steps 2 and 3.)

Step 4. Determine the representative persisting 12-hour dew point for each appropriate storm, as described in section 2.2.4. Since this dew point is usually outside the rain area (Figure 2.2), its distance and direction, or bearing, from the storm centre should be specified (paragraph 2.6.1.1). If wind maximization is indicated (section 2.4), select also for each storm the maximum 24-hour average speed of the wind from the moisture-inflow direction. Multiply the precipitable water (W), corresponding to the representative storm dew point, by the wind speed to obtain the representative storm moisture-inflow index (Figure 2.12).

Step 5. Determine the highest maximum persisting 12-hour dew point of record for the location of the reference dew point for the transposition site, as described in sections 2.2.5 and 2.6.1.1. Since several storms of different dates and with different reference dew-point locations must be transposed, it is recommended that the maximum dew points for the entire storm season and for the project basin and surrounding areas be determined at one time, as described in section 2.2.5. Preparation of maximum persisting 12-hour 1 000 mb dew-point maps, such as shown in Figure 2.4, is advisable. Such maps have an additional advantage in that they yield some indication of the geographic variation of PMP values in a plains area.

If wind maximization is required, survey storm wind data for highest maximum 24-hour average speed from direction of moisture source. Multiply the precipitable water (W) corresponding to the maximum persisting 12-hour 1 000 mb recorded dew point for the storm date, or within 15 days, by the maximum 24-hour average recorded wind speed for the same date to obtain a maximum moisture-inflow index, as in Figure 2.12. Here, again, it is recommended that the maximum moisture-inflow index be determined for the entire storm season at one time.

Step 6. Compute the combined transposition and maximization ratio of the precipitable water (W) for the maximum persisting 12-hour 1 000 mb dew point of step 5 for the storm date, or within 15 days of it (paragraph 2.3.1), to that for the representative persisting 12-hour 1 000 mb dew point for the storm, as described in section 2.6. If wind maximization is involved, compute the ratio of the maximum moisture-inflow index to the representative storm moisture-inflow index.

Step 7. Multiply the DAD array, such as in Table 2.1, for each storm by the appropriate precipitable-water or moisture-inflow index ratio, as determined in step 6.

Step 8. Plot the transposed, maximized DAD values of step 7 on diagrams, such as shown in Figures 2.9 and 2.10, and draw envelope curves. Use envelope curve values to construct DAD curves of PMP, as shown in Figure 2.11. Although not mandatory, storms providing control points on the PMP curves should be identified, as indicated in Figure 2.11, for convenience in selecting actual storm patterns for determining the time and spatial distribution of the PMP in calculating the design flood.

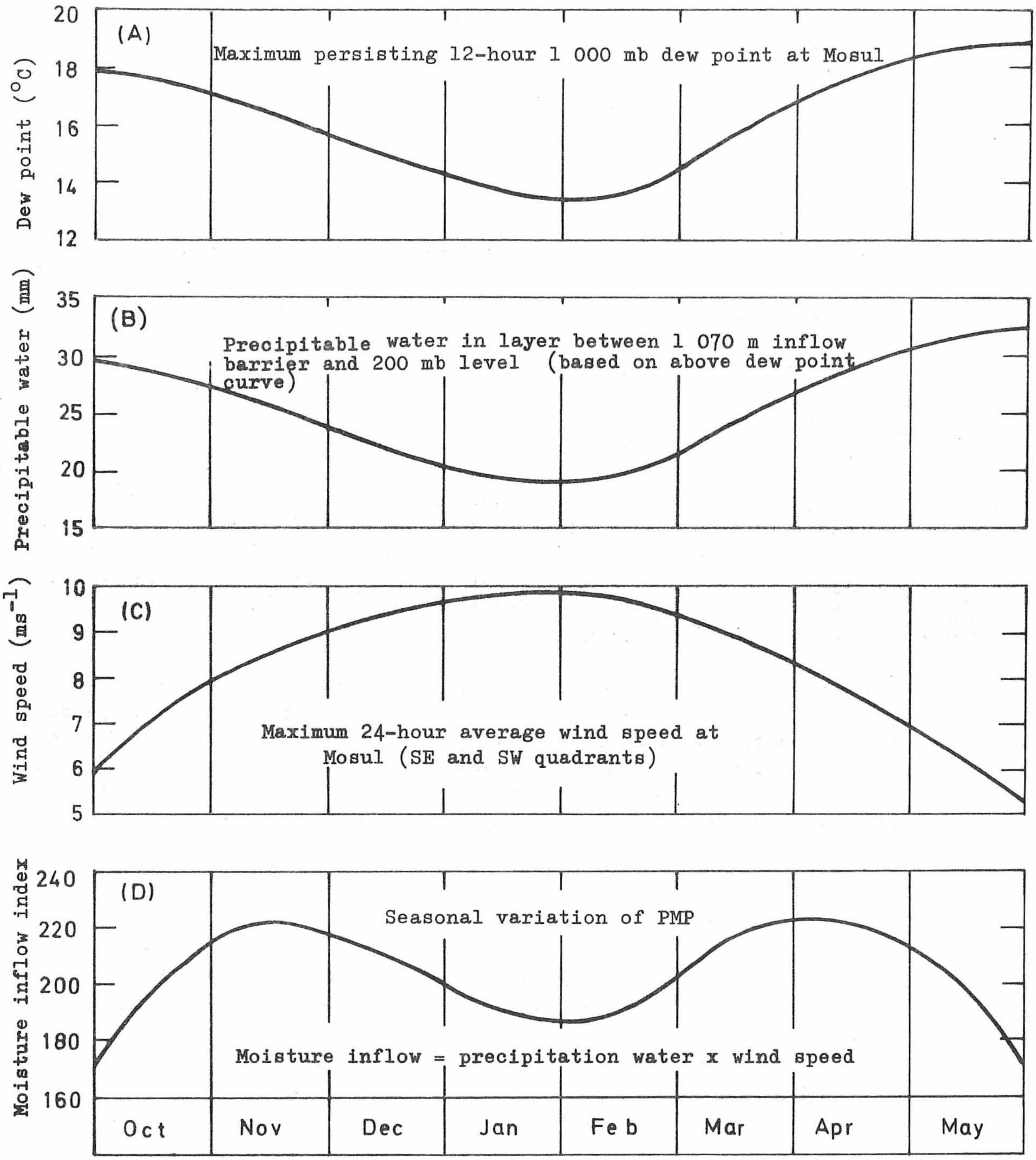

Figure 2.12 - Seasonal variation of probable maximum precipitation in the upper Tigris river basin in Iraq

2.10 Seasonal variation of PMP

2.10.1 Introduction

In those regions where the maximum flood is likely to result from a combination of snowmelt and rainfall, it is necessary to determine the seasonal variation of PMP so that various combinations for different times of the melting season can be evaluated in order to obtain the most critical. For example, in a particular region, maximized June storms may provide the controlling points for PMP but optimum combinations of accumulated snow on ground and melting rates may be found in April. It is then necessary to estimate PMP for April. Since it is not known exactly what time of year is most critical for the maximum snowmelt and rain-flood, the usual procedure is to determine the seasonal variation curve of PMP for the entire snowmelt season. The curve then permits a ready adjustment of PMP for use in assessing flood situations at various times during the melting season in order to determine the most critical flood.

There are various ways of determining the seasonal variation of PMP. The more common procedures are discussed here. Selection of a procedure depends on data available. Whenever possible, it is advisable to use several procedures in developing a seasonal variation curve. Cautionary remarks on the representativity and use of seasonal variation curves are given in section 2.13.4.

2.10.2 Observed storms

The best way for determining the seasonal variation of PMP requires a relatively large number of storms for which DAD data are available and which are fairly well distributed throughout the melting season. Different variations are usually found for small and large areas and for short and long durations. It is, therefore, important to base the seasonal variation on data consistent with the basin size and critical rainfall duration. Because of this, it is often advisable to construct a set of curves rather than a single one. The storm rainfall for a particular size of area and duration is then maximized for moisture, as described in sections 2.3 and 2.6. The maximized data are then plotted against date of storm occurrence, and a smooth envelope curve is then drawn. The rainfall scale is usually converted to a percentage scale expressing the PMP as a percentage of the peak value or the value for some particular time of year.

2.10.3 Maximum persisting 12-hour dew points

The seasonal variation of maximum persisting 12-hour dew points may be used also to determine the seasonal variation of PMP. This procedure is more applicable to localized thunderstorm PMP than to PMP for large areas and long durations. Precipitable water is computed for the individual maximum 12-hour dew points throughout the critical season, or it may be computed for values read from their seasonal variation curve, like that of Figure 2.3. A shortcoming of this procedure is that it will almost always indicate a peak PMP value in summer, even in regions where summers are dry and major storms occur in winter. It cannot be used under these conditions unless wind is considered also (see next paragraph).

2.10.4 Moisture inflow

In those regions where summers are dry and major storms occur only in the cold half of the year, the seasonal variation of maximum precipitable water (paragraph 2.10.3) gives a false indication of the seasonal variation of PMP when used by itself. A wind factor is then required to develop a representative seasonal variation of PMP.

Figure 2.12 shows a seasonal variation curve developed for PMP in the upper Tigris River Basin, where in summer there is very little rain. While the maximum dew point and precipitable water curves tend to show minimum values during the cold season climatological records show that in this region all major general-type storms occur in that season. Weather charts indicate that the heaviest precipitation occurs with surface winds in the south-east and south-west quadrants. A survey of a long record of surface winds yielded the maximum 24-hour wind curve of part C of the figure, which shows peak values in January and February. Multiplication of precipitable water values by wind speed resulted in the so-called moisture-inflow index curve of part D. The double peak was confirmed by outstanding recorded storms.

2.10.5 Daily station precipitation

An indication of the seasonal variation of PMP may be outlined readily from monthly maximum daily station rainfall amounts. The use of average maximum values for several stations rather than from a single station is advisable for the larger basin sizes. In the usual periods of rapid weather transitions, such as early fall and late spring, it may be advisable to select maximum rainfall values by half-month or 10-day periods. Here, again, the maximum values are plotted against date of occurrence, and a smooth seasonal envelope curve is then drawn. The rainfall scale is usually converted into terms of percentage, as in section 2.10.2.

2.10.6 Weekly precipitation data

Occasionally, special summaries of precipitation data may be found which can be used to derive the seasonal variation of PMP. One such summary is of average weekly precipitation for given areas, as determined by averaging station precipitation within each area for each week of the year over a long period. The seasonal variation curve of PMP may be based on an envelope of these weekly values. Obviously, a seasonal variation curve thus developed would be more applicable to PMP for long durations and large areas.

2.11 Areal distribution of PMP

2.11.1 Introduction

Once the PMP values for a particular location have been derived and presented to the hydrologist in the form of a table or enveloping DAD curves, as in Figure 2.11, he still has the problem of determining areal distribution over the project basin. It is not generally recommended that the PMP values be considered as applying to one storm, especially for the larger basins. Direct use of the PMP values may be unrealistic for the most critical design storm for two main reasons. First, the storm producing maximum rainfall over small areas within a project basin is usually of a different type from that producing maximum rainfall over the same basin as a whole. Similarly, different types of storms may obtain for different durations over the same basin. Second, the shape and orientation of the basin may be different from those permissible for the controlling isohyetal patterns.

2.11.2 Observed storm pattern

For the above reasons, the hydrometeorologist makes recommendations regarding the storm isohyetal patterns that may be applied to a basin. One or more transposed storms may provide a suitable pattern or patterns. Such a choice applies especially when both basin and storm site are topographically similar. A limitation may be placed on the rotation or displacement of the isohyetal pattern. If, as often happens, the transposed or basin storms selected provide points on the PMP DAD curves, no further adjustment may be required. If not, they may be maximized as in Figure 2.13. Current practice, however, favours bringing average depths for all durations of the storm to PMP levels, as described in section 2.11.3 for an idealized pattern. In applying the procedure to actual storms, care must be exercised to ensure that rainfall depths for areas smaller than the basin do not exceed PMP. If they do, the storm depth-area relations must be altered so that depths nowhere exceed PMP.

2.11.3 Idealized storm pattern

An alternative method for fixing the areal distribution of PMP over a basin is based on the assumption that the PMP values for all durations at the total area of the basin could occur in a single storm. This usually introduces an additional degree of maximization, because controlling values for all durations at a particular size of area are generally from several storms. In order to counter this, the precipitation values for the smaller areas within the basin are maintained at less than PMP, usually being patterned after the depth-area relations of major storms that have occurred over or near the project basin. For example, the dashed "within-basin" curves (only two shown) of Figure 2.14 set the concentration of rain within a 3 000 km^2 basin for the 6- and 24-hour durations. These curves are generally drawn for all durations by 6-hour intervals.

2.11.3.1 Areal distribution

The areal distribution of basin PMP involves the shape and orientation of its isohyetal pattern, and this may be based on observed storms. For basins up to about 20 000 km^2 in flat terrain, an oval-shaped pattern with almost any orientation is adaptable and the pattern is usually centred over the basin. For larger basins up to, and even above, the limiting size considered in this report, in the middle latitudes of the northern hemisphere, the orientation of the pattern tends to be in a general south-west — north-east direction over flat terrain. The pattern may or may not be centred over the basin, depending on what the history of major basin storms indicates.

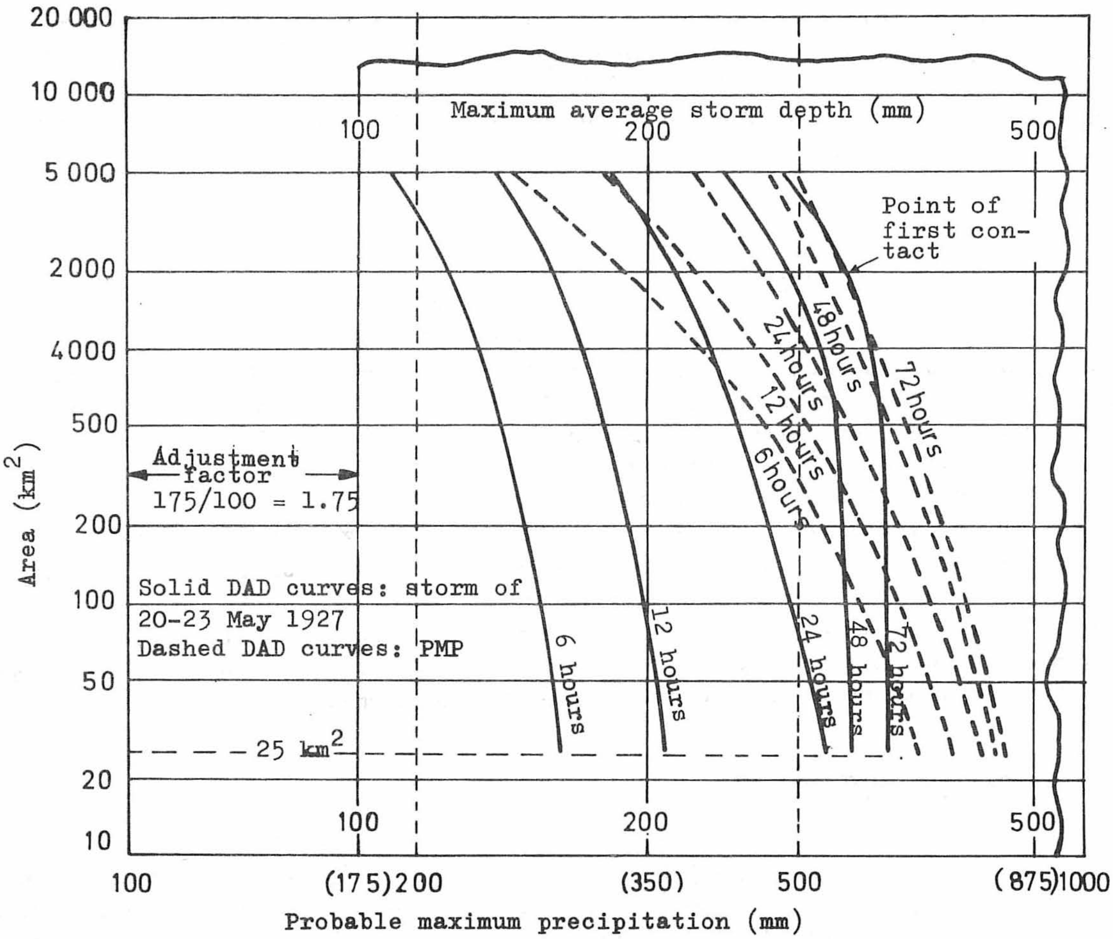

Figure 2.13 - Maximization by sliding technique. Storms not providing control points on PMP DAD curves may be maximized by plotting to same scale on separate sheets of logarithmic paper the storm and PMP DAD curves. The sheet with the storm curves is then superimposed on the other and is slid to the right until the first apparent contact between curves for the same duration is effected. The ratio of any PMP scale value to the superimposed storm scale value is the maximizing factor. Obviously, this factor adjusts the observed storm for greater rain-producing efficiency as well as for maximum moisture. Above illustration for a 5 000 km^2 basin shows point of first contact occurring between the 72-hour curves at about 2 000 km^2, but different time and spatial distributions might show point of first contact for another duration and/or size of area

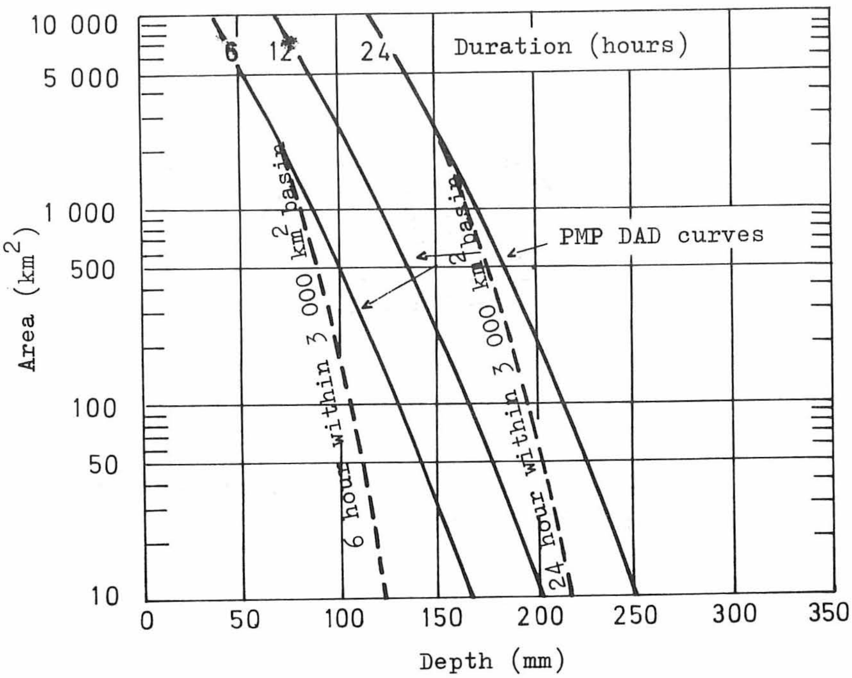

Figure 2.14 - Example of enveloping depth-area-duration curves of probable maximum precipitation and within-basin storm rainfall depths for a 3 000 km^2 basin

2.11.3.2 Example

The critical storm pattern is usually constructed on the assumption that the largest volume of rain over the basin will produce the most critical design flood. Hypothetical isohyets are drawn more or less congruent to the basin boundaries (Figure 2.15), and the rain values, or labels, for the isohyets are determined by a procedure that is essentially a reversal of the usual DAD analysis. For example: given the 6-hour PMP and "within-basin" DAD curves of Figure 2.14, determine the isohyetal values for the critical storm pattern superimposed on the outline of the 3 000 km^2 basin of Figure 2.15. Table 2.2 shows how the isohyetal profile is computed, and the results are shown in Figure 2.16. The required isohyetal values are obtained as shown in Table 2.3.

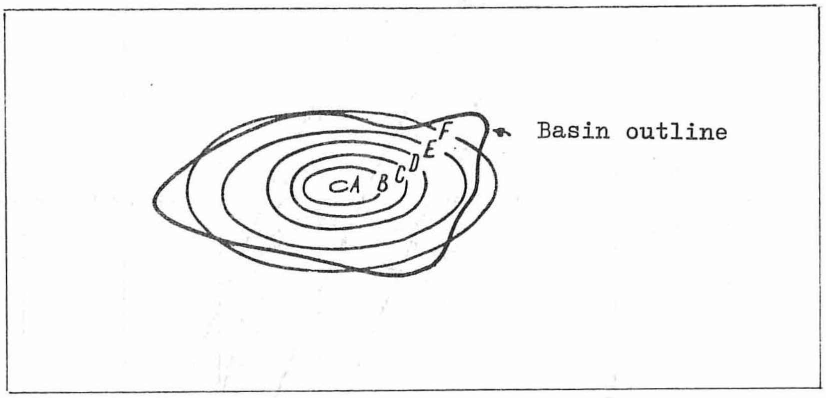

Figure 2.15 - Critical isohyetal pattern over 3 000 km^2 basin

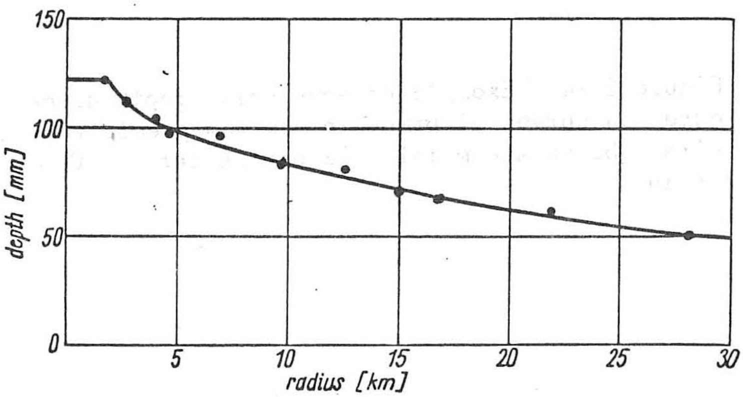

Figure 2.16 - Isohyetal profile constructed from data in columns 6 and 8 of Table 2.2

Table 2.2 - Isohyetal profile computation

(1) Total area km²	(2) Net area km²	(3) Average depth mm	(4) Accumulated rain volume km² mm	(5) Net rain volume km² mm	(6) △ Volume / △ Area mm	(7) Average area km²	(8) Equivalent circle radius km
10	10	122	1 220	1 220	122	10	1.8
40	30	113	4 520	3 300	110	25	2.8
60	20	110	6 600	2 080	104	50	4.0
80	20	107	8 560	1 960	98	70	4.7
100	20	105	10 500	1 940	97	90	5.3
200	100	100	20 000	9 500	95	150	6.9
400	200	92	36 800	16 800	84	300	9.8
600	200	88	52 800	16 000	80	500	12.6
800	200	84	67 200	14 400	72	700	15.0
1 000	200	81	81 000	13 800	68	900	16.9
2 000	1 000	71	142 000	61 000	61	1 500	21.9
3 000	1 000	64	192 000	50 000	50	2 500	28.2

Column 1. Standard size areas.

Column 2. Successive subtraction of column items.

Column 3. Maximum average depths from 6-hour "within-basin" curve of Figure 2.14.

Column 4. Product of columns 1 and 3.

Column 5. Successive subtraction of column 4 items.

Column 6. Column 5 divided by column 2.

Column 7. Average of two consecutive areas in column 1.

Column 8. Radius of circle with area of column 2.

Data of columns 6 and 8 are then used to construct the curve of Figure 2.16.

Table 2.3 - Evaluation of isohyet labels of Figure 2.15

(1) Isohyet	(2) Enclosed area km^2	(3) Equivalent radius km	(4) Isohyet value mm
A	10	1.78	122
B	200	7.98	89
C	500	12.65	77
D	750	15.50	70
E	2 000	25.20	55
F	3 000	30.98	48

Column 1. Refers to isohyets of Figure 2.15.

Column 2. Areas enclosed by isohyets of Figure 2.15.

Column 3. Radii of circles equivalent in area to values in column 2.

Column 4. Labels for isohyets of Figure 2.15 as indicated by entering Figure 2.16 with radii of column 3.

2.12 Time distribution of PMP

2.12.1 Order of presentation

PMP values, whether presented in tabular form or by DAD curves, are generally given with the maximum accumulated amounts for any duration preceding all other values for the specified duration. In other words, the 6-hour PMP amount given is the maximum 6-hour increment to be found anywhere in the PMP sequence. Similarly, the amounts for 12, 18, 24 hours and longer are the maximum for the sequence. This order of presentation, however, is rarely representative of the chronological order found in actual storms. Furthermore, it often is unlikely to produce maximum runoff for the amounts of rainfall involved.

2.12.2 Chronological order based on observed storm

A more realistic, and generally more critical, chronological order is usually obtained from some storm producing critical runoff amounts and rates in or near the project basin. Table 2.4 presents an example of how the order of the 6-hour PMP increments might be rearranged to agree with the chronological order of a critical observed storm. Note that this procedure leads to much higher rainfall amounts, hence, higher runoff than would the use of a storm maximized as in paragraph 2.11.2, where usually only one maximized value equals PMP.

When it is thought that there might be more critical possible arrangements of rainfall increments than indicated by observed storms, various realistic arrangements are examined, and the more likely ones are specified. It is the responsibility of the hydrologist to determine which arrangement will produce maximum runoff.

2.13 Cautionary remarks

2.13.1 Importance of adequate storm sample

Transposition and maximization of a few storms are unlikely to yield reliable PMP estimates. It is important that all outstanding storms recorded over the project basin and areas of transposability be used in making such estimates. If comparison of storms in the areas of transposability with those outside indicates that only a few storms within the areas reach the magnitude of the generally greater storms outside the areas, the transposition limits should be re-examined and relaxed, if at all possible, to include storms in the marginal areas just outside the limits originally determined.

Storm surveys and analyses should be extended to meteorologically comparable regions no matter how far removed from the project basin. If synoptic storm types are kept in mind, far distant areas of the world may sometimes provide better clues to PMP than nearby areas. This not only applies to precipitation data but to other factors instrumental in developing concepts basic to understanding of storm precipitation-producing mechanisms.

Table 2.4 - Chronological distribution of PMP for a hypothetical 3 000 km^2 basin

Duration hr	PMP mm	6-hour increments		Maximum accumulation
		PMP	Arranged*	
6	284	284	16	284
12	345	61	28	345
18	384	39	20	384
24	419	35	12	419
30	447	28	39	431
36	467	20	61	451
42	483	16	284	479
48	495	12	35	495
54	505	10	5	500
60	513	8	8	508
66	521	8	10	518
72	526	5	8	526

*Increments in fourth column assumed to be arranged according to sequence of increments in critical storm producing maximum runoff in project basin. Note that maximum summation of increments in last column for any given duration may be less than or equal to, but not more than, the summation of PMP increments for the same duration. Thus, for example, the maximum 24-hour amount in the last column is equal to the PMP value of 419 mm (39+61+284+35), but the maximum 30-hour value is only 431 mm (12+39+61+284+35), whereas the 30-hour PMP value is 447 mm. Actually, in this example, only the 6-, 12-, 18-, 24-, 48- and 72-hour accumulations equal the PMP values.

The greater the number of carefully selected extreme storms transposed and maximized, the greater the reliability of the resulting PMP estimates. Under ideal conditions, some two dozen major storms might be critical for determining PMP. Of these, probably fewer than half a dozen might provide control points on the PMP DAD curves.

2.13.2 Comparison with record rainfalls

The final results of any PMP estimate should always be compared with observed record values. The world record values of point rainfall, presented in Annex 2, very probably approach PMP magnitude, and estimates appreciably exceeding these values, say by 25 per cent or more, are likely to be excessive. Most estimates of point PMP would be lower than these record values for durations of, say, four hours and longer since few basins are so favourably located as to experience rainfalls of these record magnitudes.

Table A.2.3 presents enveloping values of DAD data from over 700 storms in the United States. Note that all but one value are from storms in the southern portion of the country near the moisture source, which is the Gulf of Mexico. These enveloping values from such a large sample of major storms very probably approach PMP magnitude for this region, especially for areas larger than about 25 km^2. On the other hand, they exceed PMP magnitude in those regions farther removed from the moisture source.

2.13.3 Consistency of estimates

PMP estimates for various basins in a climatically homogeneous region should be compared for consistency. Appreciable differences should be studied to see if they are supported by climatic or geographic factors. If not, it can be concluded that the differences are not valid and the various steps involved in the procedure for estimating PMP should be re-examined thoroughly. When PMP estimates are made basin by basin at various times, consistency is difficult to maintain. For achieving consistency, the generalized estimates approach, described in Chapter 5, is recommended.

2.13.4 Seasonal variation

Any one of the procedures described in section 2.10, except possibly that described in paragraph 2.10.2, may result in seasonal curves of PMP that are obviously misleading. For this reason, it is advisable to try several procedures to see if there is agreement between the resulting seasonal variation curves. Judgment on whether a derived curve is representative or not should be based on a comparison with actual storms observed at various times during the critical season.

As mentioned in section 2.10, the seasonal variation of PMP varies with duration of storm rainfall and size of area, and several seasonal variation curves may have to be derived for various durations and areas. Also, a seasonal variation curve does not imply that maximized storms can be transposed in time without regard to seasonal limitations on storm types. The curve may be used only to adjust the level of PMP to various times of the year. Storm types and patterns, however, differ from month to month, and a July storm, for example, is rarely adaptable to April conditions. Storm transposition in time is usually limited to 15 days, but a longer period, say, one month, may be justified when storm data are sparse.

2.13.5 Areal distribution

Two methods of establishing the areal distribution of what may be termed the PMP storm were described in section 2.11. The first, which involves the use of an observed storm pattern maximized by the "sliding technique" (section 2.11.2), yields conservative values, since the storm thus maximized usually equals PMP for only one duration and size of area. The second method, which is used with idealized storm patterns, requires PMP values for the basin area to be equalled for all durations (section 2.11.3). For a large basin, it is unlikely that any one storm would provide PMP values for all durations, so that, in effect, the assumption that it could is an overmaximization. In order to compensate for this, values for areas smaller than the total basin area are set at less than PMP by the use of "within-basin" depth-area curves shaped according to observed storms. The larger the basin, the larger is the difference between PMP and "within-basin" curve values for any given area smaller than the basin (Figure 5.31). Conversely, the difference decreases as basin size decreases, so that for basins of no more than a few hundred square kilometres, the areal distribution is usually accepted as conforming to the PMP curves.

If meteorological conditions are the same, there is no reason why the rainfall potential over, say, a 100 km^2 area in a 25 000 km^2 basin should be less than that over a 100 km^2 area in a 5 000 km^2 basin. The reason that "within-basin" curves indicate lesser small-area depths as basin size increases is that they are patterned after actual storms and reflect actual distributions. The effect of small-area depths on total basin rainfall volume decreases as basin size increases.

An important restriction on construction of depth-area curves is that their slopes should nowhere indicate a decrease in rainfall volume with increasing area. This applies to all depth-area curves, including PMP.

While most examples of PMP estimation presented in this manual involve areal distribution based on "within-basin" curves, it should not be inferred that this method is recommended. Whether the areal distribution is based on an observed storm maximized by the "sliding technique," on "within-basin" curves, on PMP depth-area curves, or on other methods depends on the safety factor required in the design of a hydrological structure. The areal distribution to be used is usually selected by the hydrological engineer. If he wants the most liberal design values, he will select areal distribution based on PMP curves. If not, he will select another method yielding lower design values. In making his selection, the engineer receives guidance from the hydrometeorologist. For example, the storm patterns used for maximizing by the "sliding technique" or for deriving "within-basin" curves are selected by the hydrometeorologist, who may also provide advice on how the patterns may be placed on the problem basins.

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CHAPTER 3

ESTIMATES FOR OROGRAPHIC REGIONS

3.1 Precipitation in mountainous regions

3.1.1 Orographic influences

The effects of topography on precipitation have been studied for many years. Observations of precipitation and runoff in mountainous terrain in many parts of the world show a general increase of precipitation with elevation. Several features of the increase can be discussed separately.

First there is the increase on windward slopes due to forced lifting of air over mountains. The magnitude of the effect on precipitation varies with the direction and speed of the moist air flow, and with the extent, height, and regularity of the mountain barrier. Breaks in ridges, or passes, reduce the amount of lifting. Other factors are extent and height of lower mountains or hills upwind of a slope.

Concomitant with increased precipitation on windward slopes is the decrease on lee areas. Immediately to the lee of ridges, however, is a spillover zone, where precipitation produced by the forced ascent of moist air over windward slopes can be as great as on the ridge. Because of the relatively slow fall velocity of snowflakes, spillover extends much farther beyond the ridge for snow than it does for rainfall.

A second feature of orographic precipitation, indicated by theory and supported by observations, is that first slopes or foothill regions are preferred locations for the initiation of showers and thundershowers. This effect results from stimulation of convective activity in unstable air masses by an initial and relatively small lift. Observational data are often too sparse to verify this phenomenon because of the more obvious effects of higher slopes nearby. Coastal station observations sometimes exhibit the effects of small rises in elevation. For example, a comparison of rainfalls at San Francisco, California, and Farallon Island, approximately 40 km off the coast near San Francisco Bay, showed that, in major storms, rainfall is about 25 per cent greater at San Francisco. This effect was taken into account in a PMP study for the north-western United States [10].

3.1.2 Meteorological influences

Experience has shown that general storm precipitation resulting from atmospheric systems that produce convergence and upward motion is just as important in orographic regions as on the plains. Reports of thunderstorms and passages of weather systems during large-area storms on high mountain ranges are an indicator of the dual nature of precipitation in orographic regions. Radar, for example, has tracked bands of precipitation moving across the coastal hills and Central Valley of California into the high Sierra Nevada [12].

3.1.3 Mean annual and seasonal precipitation

Mean annual and seasonal precipitation for mountainous terrain can be influenced greatly by the varying frequency of relatively light rains. Some weather situations produce precipitation on mountains when little or no precipitation is observed in valleys, and storm precipitation generally has longer durations in the mountains. Thus, the variation indicated by mean annual or seasonal precipitation maps is not necessarily a reliable index of geographic variation in PMP unless adjusted for these biases. An adjustment technique frequently used is based on the mean number of rainy days at stations in the project area and a map showing the average station, or point, precipitation per rainy day (which is usually defined as any day with measurable precipitation, but a higher threshold value, say 2 mm, is sometimes used). The most representative mean annual and seasonal precipitation maps are those based on other data in addition to precipitation [2, 6] and such maps should be used whenever possible.

3.1.4 Storm transposition

Because of the dual nature of precipitation in mountainous regions, the similarity between storm precipitation patterns and topography is limited, varying with the precipitation-producing factors involved. Nevertheless, in mountainous terrain, orographic influences on precipitation usually predominate, especially in major storms. For this reason, caution should be exercised in transposing storms in such regions because their precipitation patterns are usually intimately linked to the orography where they were observed.

3.1.5 Probable maximum precipitation

PMP estimates for orographic regions must be based on two precipitation components: (1) orographic precipitation, which results from orographic influences, and (2) convergence precipitation, which results from atmospheric processes presumably independent of orographic influences. Both components must be evaluated in making PMP estimates.

3.1.5.1 Orographic separation method

The orographic separation method consists of estimating each precipitation component separately and then adding them, keeping in mind some necessary restrictions on their addition [8]. The method, which is described in section 3.2, involves the use of an orographic model for evaluating the orographic component.

3.1.5.2 Modification of non-orographic PMP for orography

Another approach is to estimate PMP for the relatively flat regions adjoining the mountains. Modifications for terrain influences are then introduced on the basis of differences in storm rainfall data, both in the project basin and surrounding areas, and on sound meteorological judgment derived from storm analyses [3, 4, 5, 11]. The procedure is described in section 3.4 and Chapter 5.

3.1.5.3 Examples of procedures

The remainder of this chapter presents details on procedures used in applying the methods mentioned in the two preceding paragraphs. The general principles involved are discussed, and examples given from published reports. Thus, the examples necessarily are for a particular set of conditions; namely, a certain amount of available data, certain terrain characteristics, and, last but just as important, the meteorological characteristics of the major storms in the regions for which the studies were made.

3.2 Orographic separation method

3.2.1 Introduction

The orographic separation method for estimating PMP makes use of an orographic model for computing orographic storm precipitation. The conditions under which the model may be used have been found to be relatively limited, and caution in its use is advised. Despite its limited applicability, a great deal of space is devoted here to its description and use as these have never yet been published with the degree of detail allotted to other procedures described in available reports on PMP estimates. The evaluation of the convergence component of storm precipitation for the orographic separation method is described in this section also.

3.2.2 Orographic model

Precipitation released when moist air is forced over a relatively unbroken mountain ridge is the result of a basic process which can be idealized and treated as a two-dimensional problem. The air passing over the mountain crest must accelerate since there is a shallower layer within which air from a deeper upwind layer must be passed. This process has led to an orographic precipitation model in which the air flow, assumed to be laminar, is lifted over the mountain ridge. The model is a storage evaporation in that the resulting precipitation is the difference between the water vapour inflow at the base of the mountain range and the outflow above the ridge.

At some great height, called the nodal surface, air flow is assumed essentially horizontal. The height at which this occurs can be computed theoretically [1]. In general, this height is between 400 and 100 mb for moderately high barriers. A simplified diagram of inflow and outflow winds over a mountain barrier is shown in Figure 3.1.

The model considers the flow of air in a vertical plane at right-angles to a mountain chain or ridge. It is what is termed a two-dimensional model. The plane has a "y" co-ordinate in direction of flow and a "z" co-ordinate in the vertical. The flow may represent an average over a few kilometres or tens of kilometres in the transverse, or "x", direction, which does not appear explicitly in the model. The wind at ground level moves along the surface. The slope of the air streamlines above a given point on the mountain slope decreases with height, becoming horizontal at the nodal surface.

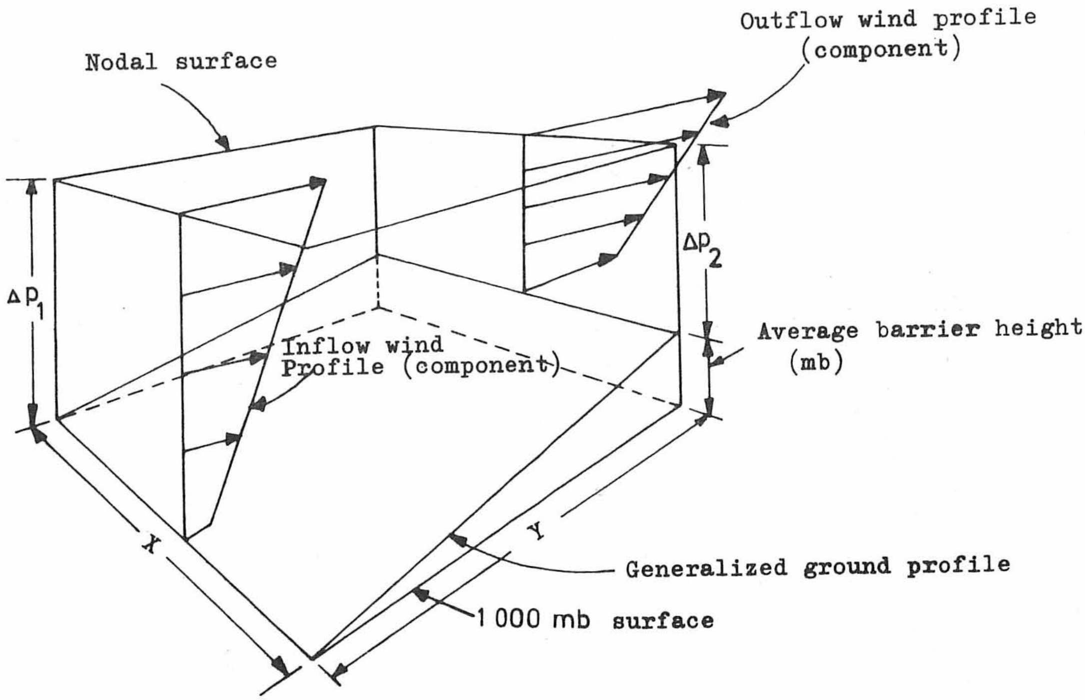

Figure 3.1 - Simplified inflow and outflow wind profiles over a mountain barrier

3.2.2.1 Single layer model

If it is assumed that the air is saturated and that temperature decreases along the rising streamlines at the moist adiabatic rate, and the flow is treated as a single layer of air between the ground and the nodal surface (Figure 3.2), the rate of precipitation is then:

$$R = \frac{\bar{V}_1 \left(W_1 - W_2 \frac{\Delta p_1}{\Delta p_2} \right)}{Y} \qquad (3.1)$$

where R is the rainfall rate in cm sec^{-1}; $\bar{V}_1$, the mean inflow wind speed in cm sec^{-1}; W_1, W_2, the inflow and outflow precipitable water (liquid water equivalent) in cm; Y, the horizontal distance in cm; and Δp_1, Δp_2, the inflow and outflow pressure differences in mb.

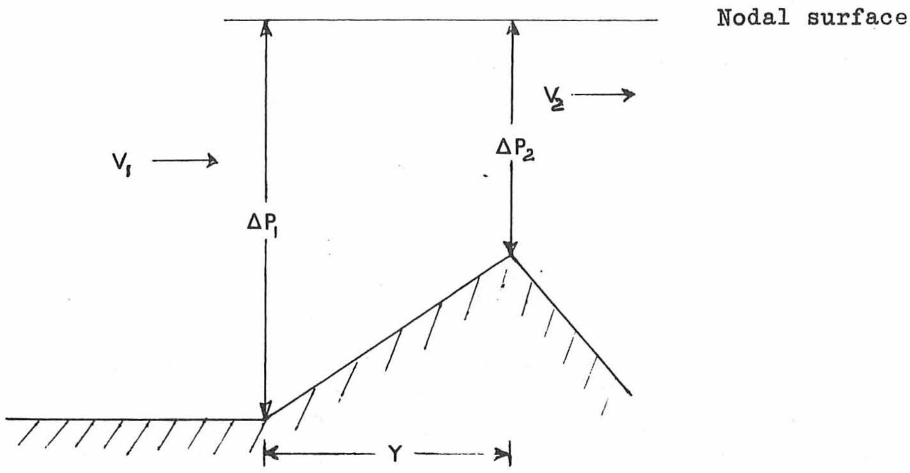

Figure 3.2 - Single layer, laminar flow, wind model

Equation (3.1) is a storage equation, i.e., precipitation equals inflow of water vapour minus outflow of water vapour. It may be derived as follows. Consider the mass transport through the slice of space bounded by two identical vertical planes, as in Figure 3.2, a short horizontal distance, s, apart. The storage equation for water vapour is:

$$M_r = (M_v)_1 - (M_v)_2 \tag{3.2}$$

where M_r is the rate of conversion of water vapour to precipitation in gm sec^{-1}; $(M_v)_1$, the rate of inflow of water vapour in gm sec^{-1}; and $(M_v)_2$, the rate of outflow of water vapour in gm sec $^{-1}$.

These terms are:

$$M_r = RYs_\rho, \tag{3.3}$$

$$(M_v)_1 = V_1W_1s_\rho, \tag{3.4}$$

$$(M_v)_2 = V_2W_2s_\rho, \tag{3.5}$$

where ρ is the density of water, which is 1.0 gm cm $^{-3}$. The mass of air flowing in equals the mass flowing out if no allowance is made for the mass of precipitation which falls, which is relatively very small and may be neglected. The continuity equation is expressed by

$$\bar{V}_1\Delta p_1 = \bar{V}_2\Delta p_2 . \tag{3.6}$$

Combining the last five equations and solving for R yields equation (3.1).

3.2.2.2 Multiple layer model

Greater precision requires dividing the air into several layers of flow, as in Figure 3.3, rather than treating it as a single layer. Equation (3.1) applies to each of these layers. Total precipitation is then obtained by adding the rates from all layers. With several layers, it is more convenient to use the storage equation in the following form:

$$R = \frac{\bar{V}_1 \Delta p_1 (\bar{q}_1 - \bar{q}_2)}{Y} \frac{1}{g\rho}, \qquad (3.7)$$

where $\bar{V}_1$ and Δp_1 refer to the inflow in a particular layer, and $\bar{q}_1$ and $\bar{q}_2$ are the mean specific humidities, in gm kg^{-1}, at inflow and outflow, respectively. Mixing ratio, w, is often substituted for specific humidity, q. The terms g and ρ refer respectively to acceleration of gravity in cm sec^{-2} and density of water in gm cm^{-3}.

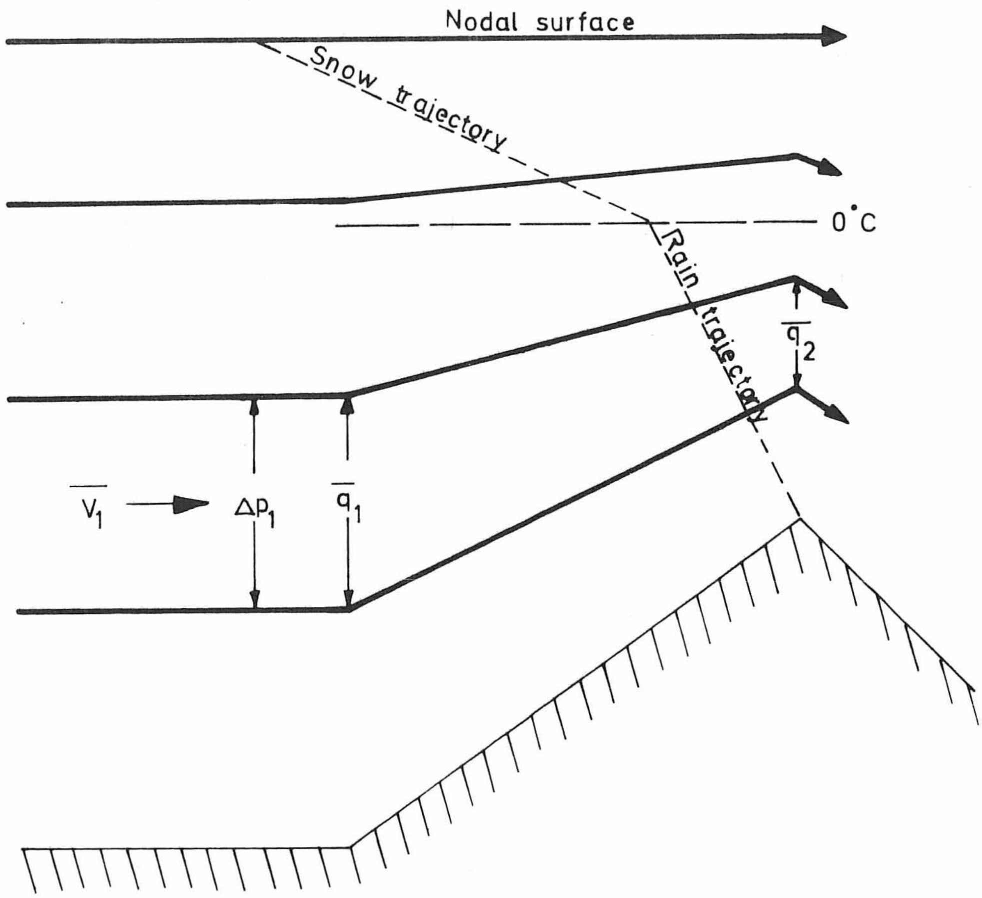

Figure 3.3 - Multiple layer, laminar flow, wind model

Equation (3.7) derives from the relation between specific humidity and precipitable water:

$$W = \frac{\bar{q}\,\Delta p}{g\rho}. \tag{3.8}$$

Substituting this relation into equation (3.1) yields

$$R = \frac{V_1 \left(\frac{q_1 \Delta p_1}{g\rho} - \frac{q_2 \Delta p_2}{g\rho} \frac{\Delta p_1}{\Delta p_2} \right)}{Y} \tag{3.9}$$

which reduces to equation (3.7).

An approximate relation often substituted for equation (3.7) is:

$$R \approx \frac{0.0102\, \bar{V}_1\, \Delta p_1\, (\bar{w}_1 - \bar{w}_2)}{Y} \tag{3.10}$$

where R is the rainfall rate in mm hr^{-1}; $\bar{V}_1$ is the mean inflow wind speed in knots; Δp_1 is the pressure difference between the top and bottom of an inflow layer in mb; $\bar{w}_1$ and $\bar{w}_2$ are the mean mixing ratios in gm kg^{-1}, at inflow and outflow, respectively; and Y is the horizontal length of the slope in nautical miles (n miles).

Relation (3.10) derives from the approximate relation between mean mixing ratio, $\bar{w}$, and precipitable water, W:

$$W \approx 0.0102\, \bar{w}\, \Delta p \tag{3.11}$$

where W is in mm; $\bar{w}$ in gm kg^{-1}; Δp in mb; and the coefficient, 0.0102, has the dimensions mm mb^{-1} kg gm^{-1}. Substituting this relation into equation (3.1) and using larger units of V and Y yields relation (3.10).

3.2.2.3 Precipitation trajectories

The distribution of precipitation along a windward slope requires construction of snow and raindrop trajectories from the level of their formation to the ground. These trajectories are considered along with streamlines of the air flow over a ridge, as shown in Figure 3.3. The computation of precipitation trajectories is described in the following example of a test of the orographic model against observed storm rainfall.

3.2.3 Test of orographic model on observed storm

The following example of the use of the model was selected from PMP studies for the Sierra Nevada and Cascade Range near the west coast of the United States [8, 10]. Figure 3.4 shows a map of the test area with some of the precipitation stations. Figure 3.5 shows the smoothed average ground elevation profile used for the computations. The elevations of the precipitation stations are plotted to show how well they

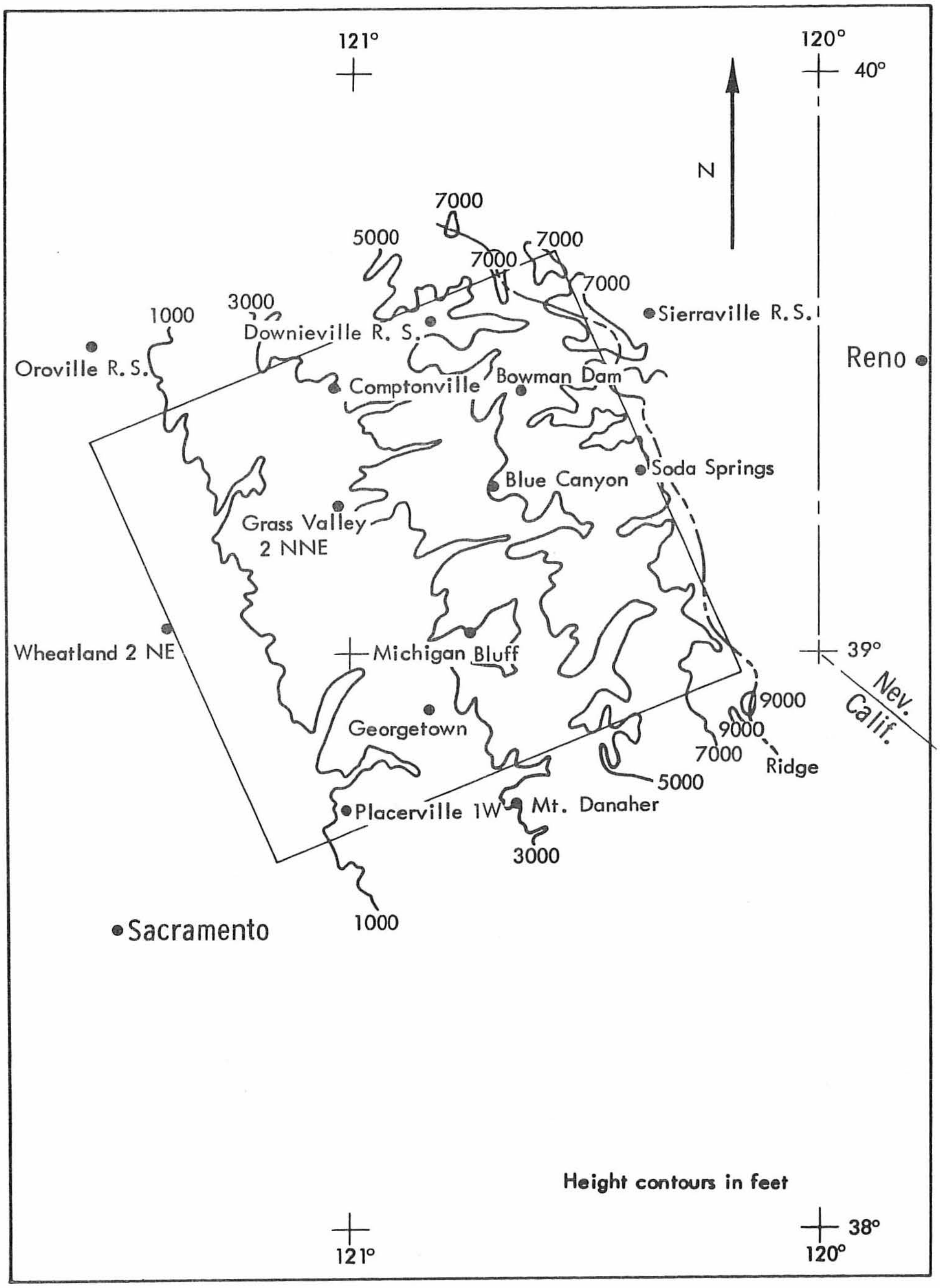

Figure 3.4 - Blue Canyon orographic model test area in California

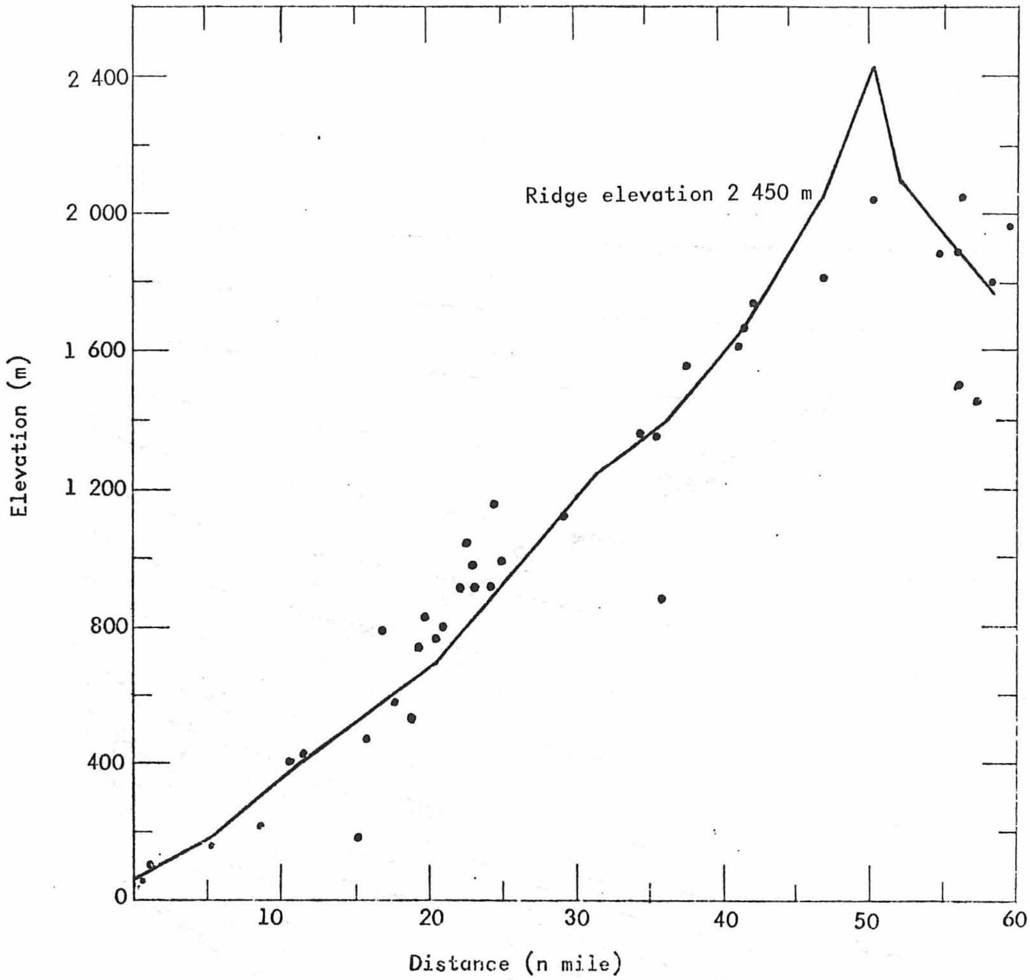

Figure 3.5 - Precipitation station elevations relative to adopted ground profile for test area of Figure 3.4

fit the profile. The storm period selected for testing was the six-hour period ending at 2000Z, 22 December 1955. The 1500Z, 22 December upper-air sounding at Oakland, Calif., approximately 160 km south-west of the inflow end (south-west side) of the test area, was used for inflow data. Precipitation computations will be shown for the last segment, or portion, of the windward slope near the crest. The following steps are recommended in computing orographic precipitation over the slope.

3.2.3.1 Ground profile

Determine the ground profile of the area under consideration and divide into segments at each break in the profile. Long segments may be subdivided. In Figure 3.6, since the slope is fairly uniform, the first nine segments, or legs, have been made of equal length, 6 statute miles or 5.2 n miles. The length of the last leg is 4 statute miles or 3.5 n miles, so total distance from inflow to outflow is 50.3 n miles.

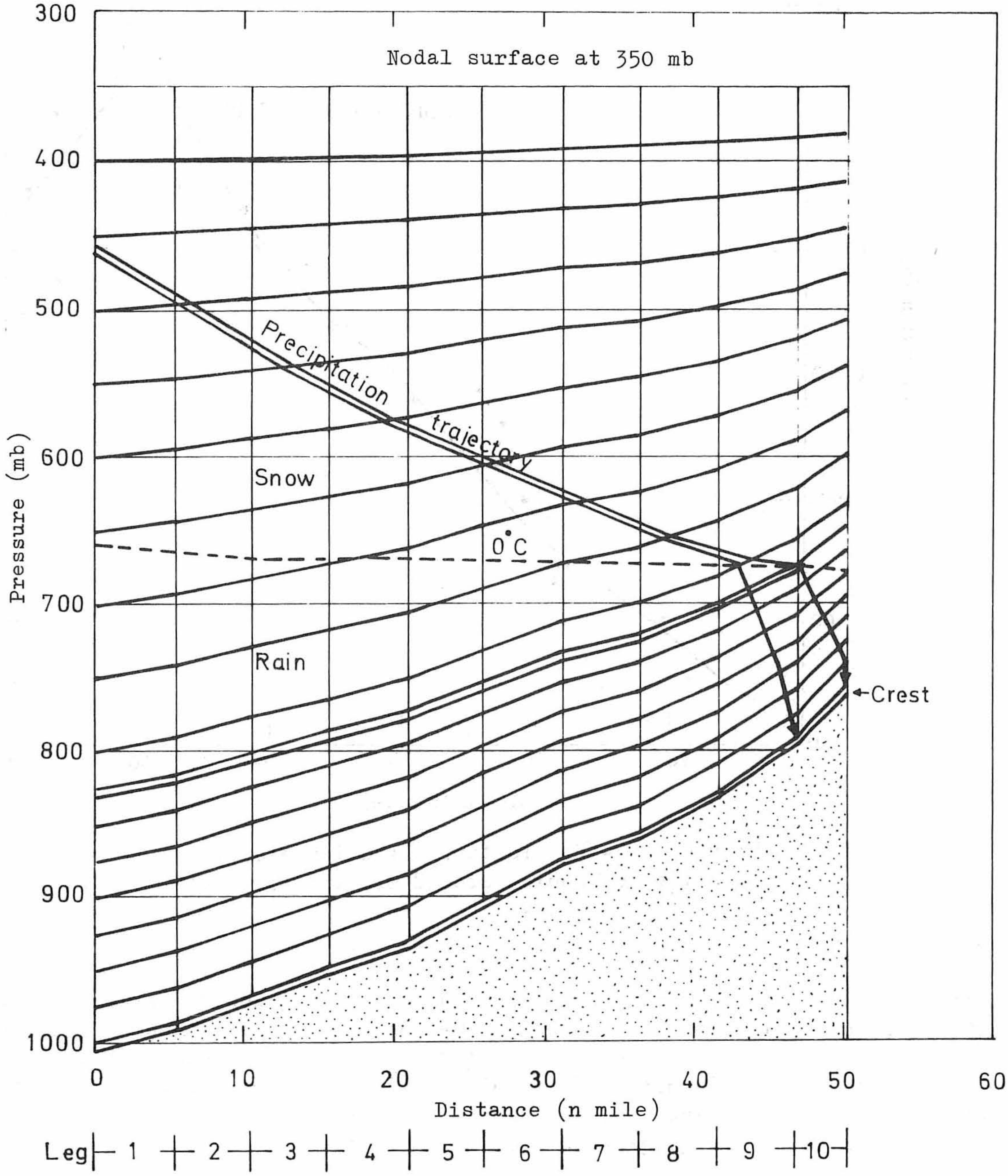

Figure 3.6 - Air streamlines and precipitation trajectories for test case

Convert heights of ground profile (Figure 3.5) to pressures by means of the pressure-height curve constructed from the inflow sounding of pressure, temperature, and relative humidity. Plot these pressures at the end of each leg, and draw ground profile as shown in Figure 3.6. (Until some way is found to take downslope motion of air into account in computing precipitation, it is recommended that any downslopes in the ground profile be drawn horizontal.) Construct verticals at the inflow and outflow ends of the model and at the end of each leg.

3.2.3.2 Inflow data

The inflow data used in the example are tabulated in the first eight columns of Table 3.1. These data were obtained from the sounding. The wind speeds are the components normal to the mountain ridge, i.e., $V = V_o \cos \alpha$, where V_o is the observed wind speed from the observed direction and α is the angle between the observed direction and the normal to the ridge.

3.2.3.3 Air streamlines

Space the streamlines at the inflow vertical in the manner indicated in Figure 3.6. There, the first streamline above the surface streamline is set at 1 000 mb. Streamlines are then spaced at 25 mb intervals up to the 800 mb level, thence at every 50 mb up to the nodal surface, which is assumed to be at 350 mb. Streamlines at the outflow vertical and intermediate verticals are spaced in proportion to the spacing at inflow. Spacing may be done either graphically or by mathematical interpolation.

3.2.3.4 Freezing level

As the air travels along any streamline, its pressure, temperature and mixing ratio at any point on the streamline may be determined from a pseudo-adiabatic chart. Determine the pressure at the freezing point on those streamlines where the zero °C temperature occurs between inflow and outflow. (See discussion of Table 3.2 in section 3.2.3.5.) Plot these points on their respective streamlines, and draw freezing line as shown in Figure 3.6. Precipitation is assumed to fall as snow above the freezing line and as rain below.

3.2.3.5 Precipitation trajectories

The path followed by falling precipitation particles is determined by three components: (1) vertical fall due to gravity, (2) horizontal drift caused by the horizontal component of the wind, and (3) vertical rise resulting from the upward component of the wind as it flows along the streamlines.

The average falling rate of precipitation particles in orographic storms affecting the test area has been taken as 6 ms^{-1} for rain and 1.5 ms^{-1} for snow. For computational purposes, these values have been converted to 2 160 and 453 mb hr^{-1}, respectively.

The horizontal drift of precipitation particles while falling from one streamline to another is $\bar{V}\Delta p$/rate of fall, where $\bar{V}$ is the mean horizontal wind speed, in knots, in the layer between streamlines; Δp is the thickness of the layer in mb; and rate of fall is in mb hr^{-1}. Since $\bar{V}\Delta p$ is constant between any two streamlines, drifts computed at inflow may be used anywhere between the same two streamlines. In Table 3.2, horizontal rain drift (DRR) and horizontal snow drift (DRS) between streamlines are shown in columns (6) and (7). Drifts are in nautical miles (n miles) since $\bar{V}$ is in knots (kn). The effect of the upward component of the wind is automatically taken into account by the slope of the streamlines.

Precipitation trajectories are computed from the ground up, starting at the ends of the selected legs of the ground profile. Plotting points for two trajectories are computed in Table 3.2: one, called upper (UT), beginning at outflow, or 50.3 n miles from inflow; and the other, called lower (LT), beginning at the end of the ninth leg, or 46.8 n miles from inflow. Columns (8) and (9) of Table 3.2 give accumulated horizontal drifts from the vertical passing through the ground point of each of these trajectories. Columns (10) and (11) give corresponding distances from the inflow vertical.

Rain drift is used below the freezing level; snow drift, above. By coincidence, the lower trajectory (Figure 3.6) reaches the freezing level approximately where the latter intersects a streamline. The upper trajectory, however, reaches the freezing level between the 850 and 825 mb inflow streamlines. Hence, a streamline passing through the intersection of this trajectory and the 0°C line is constructed. This streamline intersects the inflow vertical at 831 mb. Since the snow drift in the 831 to 825 mb layer is 0.65 n miles (Table 3.2), the total drift measured from the outflow vertical to the 825 mb streamline would be 2.95 + 0.65 = 3.60 n miles, which would take the trajectory below the freezing level. Hence, total drift was assumed to be 3.47 n miles, which means that the drift within this layer was assumed to be 0.52 n miles rather than 0.65. Since the snow in this layer is probably very wet, the falling rate is likely to be between that for snow and that for rain, and the above assumption appears warranted.

3.2.3.6 Precipitation computation

After constructing the precipitation trajectories, compute the total volume of precipitation under each trajectory, layer by layer. Subtract the total volume under one trajectory from the volume under the next higher one, and divide the difference by the horizontal area of the ground on which this volume falls to obtain the average depth over this area.

If relation (3.10) for rainfall rate is multiplied by the area, XY, it yields the 1-hour rainfall volume. The Y's in the numerator and denominator cancel, and if area width, X, is taken as 1 n mile, the 1-hour volume, R (XY), or Vol_{1-h}, under a particular trajectory is approximately

$$Vol_{1-h} \approx 0.0102\ \bar{V}_1 \Delta p_1 \ (\bar{w}_1 - \bar{w}'), \tag{3.12}$$

where $\bar{w}'$ is the mean outflow mixing ratio at the trajectory (see $\bar{q}'$ in Figure 3.3).

Table 3.1 - Computation of orographic precipitation over leg 10 of Blue Canyon, California, test area for the 6-hour period 1400-2000Z, 22 December, 1955
(Hand computation, using 1500Z, 22 December sounding at Oakland, California, as inflow data and assuming a nodal surface of 350 mb)

Inflow data																$\Delta\bar{w}_{LT}=$		$\Delta\bar{w}_{UT}=$	
p (mb)	T (°C)	RH (%)	V (kn)	$\bar{V}$ (kn)	$\bar{V}\Delta p$	w_s (g kg^{-1})	w_I	p_c	p_{LT}	w_{LT}	p_{UT}	w_{UT}	$\bar{w}_I$	$\bar{w}_{LT}$	$\bar{w}_{UT}$	$\bar{w}_I - \bar{w}_{LT}$	$\bar{V}\Delta p\Delta\bar{w}_{LT}$	$\bar{w}_I - \bar{w}_{UT}$	$\bar{V}\Delta p\Delta\bar{w}_{UT}$
500	-12.3	77	61.8			2.96	2.28	475	496	2.28	495	2.28							
				59.6	2 980								2.70	2.70	2.70	0	0	0	0
550	-8.1	82	57.4			3.80	3.12	529	537	3.12	536	3.12							
				62.7	3 135								3.61	3.53	3.52	.08	251	.09	282
600	-4.2	88	67.9			4.65	4.09	583	575	3.94	574	3.92							
				62.8	3 140								4.64	4.22	4.20	.42	1 319	.44	1 382
650	-0.6	92	57.6			5.64	5.19	638	604	4.50	602	4.47							
				55.1	2 755								5.72	4.73	4.69	.99	2 727	1.03	2 838
700	2.6	94	52.6			6.64	6.24	692	630	4.95	628	4.90							
				49.8	2 490								6.69	5.18	5.13	1.51	3 760	1.56	3 884
750	5.3	95	47.0			7.50	7.13	742	656	5.40	654	5.36							
				50.1	2 505								7.55	5.51	5.45	2.04	5 110	2.10	5 261
800	7.9	95	53.1			8.38	7.96	792	672	5.61	669	5.54							
				51.4	1 285								8.20	5.75	5.57	2.45	3 148	2.63	3 380
825	9.1	96	49.6			8.79	8.44	817	688	5.88	672	5.60							
				49.2	295								8.50	5.92	5.61	2.58	761	2.89	853
831	9.4	96	48.7			8.92	8.56	823	693	5.95	673	5.62							
				47.2	897								8.75	6.09	5.69	2.66	2 386	3.06	2 745
850	10.3	96	45.7			9.30	8.93	843	703	6.22	680	5.76							
				44.2	1 105								9.13	6.34	5.86	2.79	3 083	3.27	3 613
875	11.4	96	42.7			9.71	9.32	868	718	6.45	694	5.95							
				42.7	1 068								9.46	6.51	6.00	2.95	3 151	3.46	3 695
900	12.5	94	42.7			10.20	9.59	888	732	6.57	705	6.05							
				41.9	1 048								9.69	6.59	6.06	3.10	3 249	3.63	3 804
925	13.4	93	41.1			10.52	9.79	911	746	6.60	717	6.07							
				37.6	940								9.81	6.64	6.09	3.17	2 980	3.72	3 497
950	14.2	91	34.1			10.80	9.83	929	760	6.68	729	6.10							
				29.9	748								9.63	6.57	5.94	3.06	2 289	3.69	2 760
975	15.0	85	25.7			11.10	9.43	941	776	6.46	740	5.78							
				19.4	485								9.42	6.42	5.76	3.00	1 455	3.66	1 775
1 000	15.5	84	13.1			11.20	9.41	961	790	6.37	753	5.73							
				11.1	56								9.55	6.48	5.80	3.07	172	3.75	210
1 005	15.7	86	9.1			11.27	9.69	971	793	6.58	758	5.87							

	LT	UT
Σ =	35 841	39 979
6-hour volume (mm(n mile)^2) = .061 2 x Σ =	2 193	2 447
Unit-width horizontal area (n mile)^2 =	46.8	50.3
6-hour average rainfall (mm) =	47	49

6-hour average rainfall over last leg = (2 447-2 193)/(50.3-46.8) = 73 mm

Legend

RH = Relative humidity
w_s = Saturation mixing ratio
w_I = Mixing ratio at inflow
Pc = Condensation pressure
LT = Lower precipitation trajectory
UT = Upper precipitation trajectory
Meaning of other symbols obvious

The orographic model is generally used to compute rainfall by 6-hour increments, so relation (3.12) becomes

$$Vol_{6-h} \approx 0.0612\ \overline{V}_1 \Delta p_1\ (\overline{w}_1 - \overline{w}'), \qquad (3.13)$$

where Vol_{6-h} is in mm (n mile)^2; $\overline{V}_1$ in kn; Δp_1 in mb; $(\overline{w}_1 - \overline{w}')$ in gm kg^{-1}; and coefficient 0.0612 has the dimensions (n mile) h (6 h)$^{-1}$ kg gm^{-1} mm mb^{-1}.

Table 3.1 shows the computation of orographic rainfall under the two precipitation trajectories shown in Figure 3.6. The following example demonstrates how the table was prepared.

Consider the layer between the streamlines passing through inflow pressures 850 and 875 mb (Δp = 25 mb). The air at 850 mb has a temperature of 10.3°C, relative humidity 96 per cent, and horizontal component of wind speed parallel to the sides of the selected ground area of 45.7 kn. Plotting 10.3°C at 850 mb on a pseudo-adiabatic chart, the saturation mixing ratio is seen to be about 9.30 gm kg^{-1}. The actual mixing ratio is 96 per cent of this, or 8.93 gm kg^{-1}.

From Figure 3.6, the pressures where the streamline through 850 mb intersects the two precipitation trajectories are seen to be 703 and 680 mb. Following the dry adiabat through 850 mb and 10.3°C upward to where it crosses the saturation mixing ratio of 8.93 gm kg^{-1}, the condensation pressure is seen to be about 843 mb and the temperature 9.6°C (not shown). Since the air is now saturated, the moist adiabat is followed upward from this point. The saturation mixing ratio on this moist adiabat is about 6.22 gm kg^{-1} at 703 mb and about 5.76 gm kg^{-1} at 680 mb. The mixing ratio values on the 875 mb streamline at the lower and upper precipitation trajectories are found in the same way.

For the 850 - 875 mb layer, $\overline{V}$ is then seen to be 44.2 kn, $\overline{V}\Delta p$ = 1105 kn mb, $\overline{w}_1$ = 9.13 gm kg^{-1}, $\overline{w}_{LT}$= 6.34 gm kg^{-1} for the lower trajectory, and $\overline{w}_{UT}$ = 5.86 gm kg^{-1} for the upper trajectory. The decrease in mean mixing ratio of the layer from inflow to lower trajectory, $\Delta \overline{w}_{LT}$ = 2.79 gm kg^{-1} and to the upper trajectory, $\Delta \overline{w}_{UT}$ = 3.27 gm kg^{-1}. For the layer, the value of $\overline{V}\Delta p\Delta\overline{w}$ is 3 083 (n mile) h^{-1} mb gm kg^{-1} between inflow and lower precipitation trajectory and 3 613 (n mile) h^{-1} mb gm kg^{-1} between inflow and upper trajectory.

After values of $\overline{V}\ \Delta p\ \Delta\overline{w}$ are computed for all layers for all trajectories, values for each trajectory are summed and multiplied by .061 2 (n mile) h (6 h)$^{-1}$ mm mb^{-1} kg gm^{-1} to obtain values in mm (n mile)^2 (6 h)$^{-1}$. In Table 3.1 these values are 2 193 for the lower trajectory and 2 447 for the upper. Division by the areas over which these volumes fall gives average depths for those areas. Since unit width is assumed for Figure 3.6, any such area is numerically equal to the sum of the lengths of the legs between inflow and a given precipitation trajectory. For the lower trajectory this is the sum of the lengths of legs 1-9 or 46.8 (n mile)^2, which makes the 6-hour average depth over those legs 47 mm. For the upper trajectory the volume falls over legs 1-10 or 50.3 (n mile)^2, giving a 6-hour average depth of 49 mm. The volume that falls on leg 10 alone is the difference between the volumes under upper and lower trajectories or 254 mm (n mile)^2 (6 h)$^{-1}$. This is distributed over 3.5 (n mile)^2, which makes the 6-hour average depth 73 mm.

Table 3.2 - Computation of rain and snow drift for computing precipitation trajectories over Blue Canyon, California, test area (Based on sounding of 1500Z, 22 December 1955 at Oakland, California)

Inflow data p (mb)	V (kn)	$\bar{V}$ (kn)	Δp (mb)	$\bar{V}\Delta p$	DRR (n mile)	DRS (n mile)	(UT) ΣDRIFT (n mile)	(LT) ΣDRIFT (n mile)	(UT) 50.30- ΣDRIFT (n mile)	(LT) 46.80- ΣDRIFT (n mile)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
350	97.7									
		81.9	50	4 095	1.90	9.04				
400	66.1									
		68.6	50	3 430	1.59	7.57				
450	71.0						51.18*	48.55*	-.88	-1.75
		66.4	50	3 320	1.54	7.33				
500	61.8						43.85*	41.22*	6.45	5.58
		59.6	50	2 980	1.38	6.58				
550	57.4						37.27*	34.64*	13.03	12.16
		62.7	50	3 135	1.45	6.92				
600	67.9						30.35*	27.72*	19.95	19.08
		62.8	50	3 140	1.45	6.93				
650	57.6						23.42*	20.79*	26.88	26.01
		55.1	50	2 755	1.28	6.08				
700	52.6						17.34*	14.71*	32.96	32.09
		49.8	50	2 490	1.15	5.50				
750	47.0						11.84*	9.21*	38.46	37.59
		50.1	50	2 505	1.16	5.53				
800	53.1						6.31*	3.68	43.99	43.12
		51.4	25	1 285	0.59	2.84				
825	49.6						3.47**	3.09	46.83	43.71
		49.2	6	295	0.14	.65				
831	48.7						2.95	2.95	47.35	43.85
		47.2	19	897	0.42	1.98				
850	45.7						2.53	2.53	47.77	44.27
		44.2	25	1 105	0.51	2.44				
875	42.7						2.02	2.02	48.28	44.78
		42.7	25	1 068	0.49	2.36				
900	42.7						1.53	1.53	48.77	45.27
		41.9	25	1 048	0.49	2.31				
925	41.1						1.04	1.04	49.26	45.76
		37.6	25	940	0.44	2.08				
950	34.1						0.60	0.60	49.70	46.20
		29.9	25	748	0.35	1.65				
975	25.7						0.25	0.25	50.05	46.55
		19.4	25	485	0.22	1.07				
1 000	13.1						0.03	0.03	50.27	46.77
		11.1	5	56	0.03	0.12				
1 005	9.1						0	0	50.30	46.80

*Using snow drift

**Arbitrary (to keep trajectory on or above freezing line)

Legend

DRR = $\bar{V}\Delta p/2160$ = Horizontal rain drift

DRS = $\bar{V}\Delta p/453$ = Horizontal snow drift

UT = Upper precipitation trajectory

LT = Lower precipitation trajectory

3.2.3.7 Comparison of results

The above procedure has been computerized to facilitate complete computations for numerous areas and soundings. Another computerized version of the orographic model is somewhat more sophisticated than the one just described. Whereas in the example model the height of the nodal surface was assumed and an approximate method used for spacing streamlines at the outflow over a mountain crest, this second computer model uses a nodal surface and streamline spacing based on physical laws of air flow /1/. The outflow approximations used in the above example give results comparable to those of the more sophisticated model. Table 3.3 compares the results yielded by the two computerized models for each of the ten legs for a 6-hour period and by the manual application just described for the tenth leg.

Table 3.3 - Comparison of observed and compured 6-hour precipitation for the period 1400-2000Z, 22 December 1955 over Blue Canyon, California, test area

	Leg	1	2	3	4	5	6	7	8	9	10	Average 1-10
Horizontal length of leg	(n mile)	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	3.5	
Cumulative length	(n mile)	5.2	10.4	15.6	20.8	26.0	31.2	36.4	41.6	46.8	50.3	
Elevation at end of leg	(ft)	590	1 200	1 780	2 320	3 210	4 080	4 640	5 540	6 760	8 030	
	(m)	180	366	543	707	978	1 244	1 414	1 689	2 060	2 448	
Observed precipitation	(mm)	3	6	13	25	38	46	55	64	67	65	37
Machine-computed precipitation 1	(mm)	0	14	40	44	55	66	54	60	67	72	46
Machine-computed precipitation 2	(mm)	1	17	44	45	56	66	55	59	67	69	47
Hand-computed precipitation	(mm)										73	49

Elevation at beginning of first leg = 200 ft (61 m)

Notes

Machine-computed precipitation 1 used spacing of streamlines by a method developed by Myers (1).
Machine-computed precipitation 2 used spacing of streamlines between surface and 350 mb nodal surface (assumed), along any vertical, proportional to their spacing at inflow.
Hand-computed average precipitation over leg 10 and legs 1-10 based on same spacing of streamlines as machine-computed precipitation 2.

The so-called observed precipitation used in the comparison of Table 3.3 refers to the orographic component only. Ordinarily, this would be obtained by subtracting from the observed total precipitation for each leg the precipitation measured in the flat valley upwind of the test area during the 6-hour period of the test. This valley precipitation (convergence component of total precipitation), which is sometimes reduced for elevation, is attributed to atmospheric processes not directly related to orography. In the test case described, however, there was no appreciable valley precipitation so no deduction was made from observed precipitation.

3.2.3.8 Sources of error

Differences between precipitation computed by the model and observed orographic precipitation (total precipitation minus convergence component) can be attributed to two main sources: (a) errors of input to the model, and (b) sparsity and unrepresentativeness of precipitation data for checking model computation.

Input to the model. Usually, no more than two upper-air observations are made daily. Despite utmost care in interpolating for a particular storm period by referring to the more frequent surface synoptic charts, the question remains as to the representativity of instantaneous wind and moisture values for even a short period of a few hours. Such inaccuracies lead to errors in computed amounts of precipitation.

In the example given, no allowance was made for the fact that the upper-air sounding station (Oakland) is approximately 160 km from the test area, and moisture and wind values were taken directly from the sounding. Attempts to adjust for wind travel time (averaging less than two hours) did not improve results.

Observed orographic precipitation. The uneven distribution of storm precipitation, both with respect to time and space; the sparseness of the precipitation network; and the usual errors of gauge measurements make it difficult to obtain reliable averages of storm precipitation on slopes. Also, most gauges in orographic regions are located in narrow valleys or on relatively flat sites unrepresentative of nearby elevations or the generalized ground profile. Their measurements, while perhaps acceptably representative of actual precipitation at the gauge sites, are unlikely to represent with any great accuracy the average precipitation falling on the general slope. These various factors make it difficult to obtain reliable values of observed storm precipitation on a slope for comparison with model computations.

3.3 Orographic separation method for estimating PMP

Reference was made earlier to the fact that precipitation in mountainous regions consists of two components: (1) orographically induced precipitation (orographic precipitation), and (2) precipitation produced by atmospheric processes unrelated to orography (convergence precipitation). PMP is computed therefore by maximizing and adding the two precipitation components. Caution must be exercised to avoid over-maximizing.

3.3.1 Orographic PMP

The procedure used in applying the orographic model for computing the orographic component of PMP is the same as that used in testing the model (section 3.2.3) with the exception that inflow winds and moisture are maximum values.

3.3.1.1 Maximum winds

If there is a long record of upper-air winds, say 30 years or longer, an envelope of the highest recorded speeds for winds from critical directions for each month or part of month is usually adequate. The probability of occurrence of any of the envelope values may be determined by statistical analysis. Such analysis may be used also to estimate high wind speeds, say for a 50-year return period, when the record is so short as to introduce doubt as to its maximum values being representative of those to be obtained from a longer record. If the record is so short, say less than ten years, as to preclude reliable frequency analysis, maximum wind speeds may be estimated from surface pressure gradients between suitably located stations. Maximum surface winds so determined may then be used to estimate upper-air wind speeds by means of empirical relations /8/.

Figure 3.7 shows the maximum wind speed profile used for the coastal region of California. The variation with duration (Figure 3.8) was based on that of geostrophically derived winds and that of 900 mb winds at Oakland during selected storm periods.

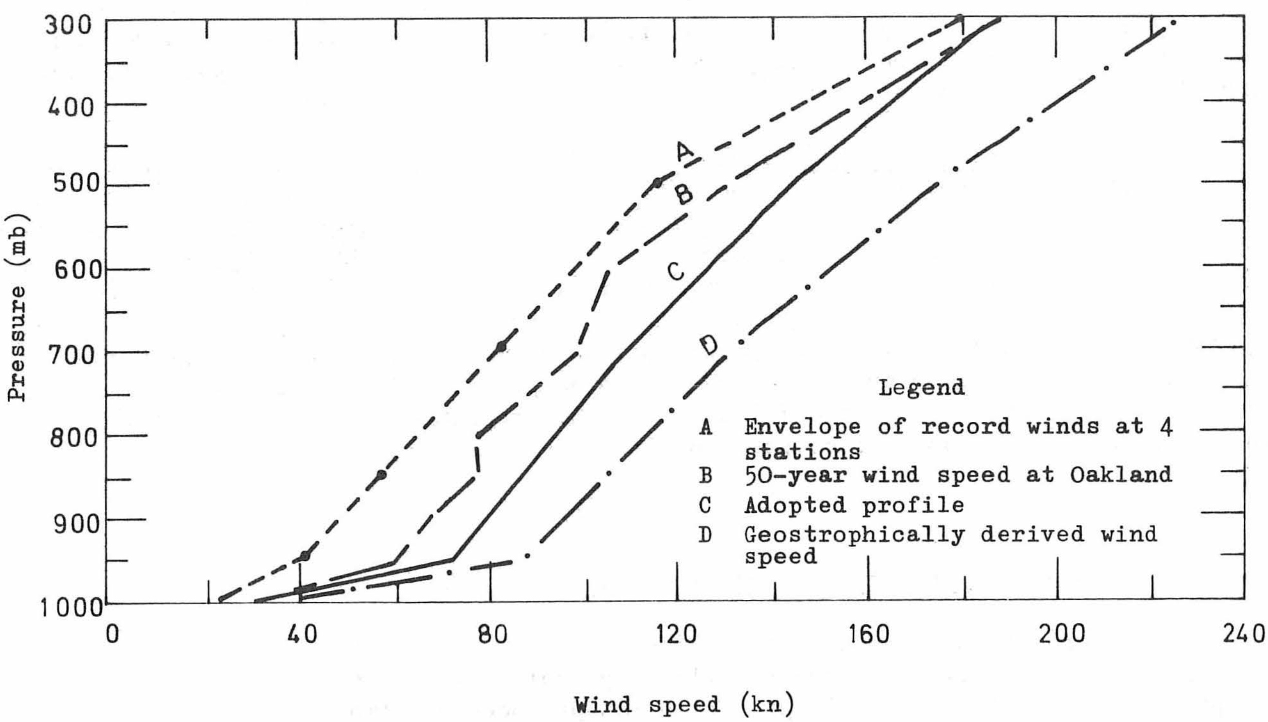

Figure 3.7 - Maximum one-hour wind profile and supporting data

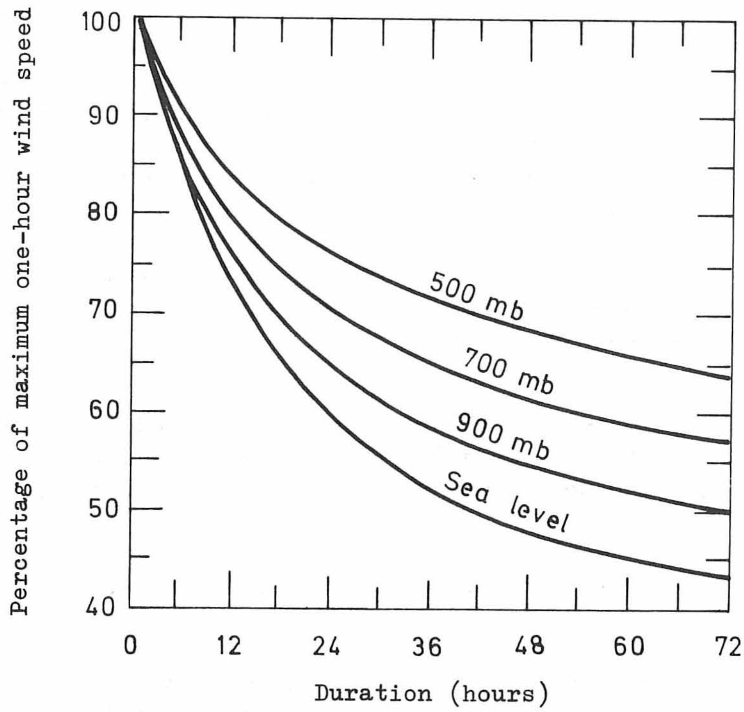

Figure 3.8 - Variation of maximum six-hour wind speed with time

3 3.1.2 Maximum moisture

Maximum values of moisture are obtained from maximum persisting 12-hour 1 000 mb dew points. A full discussion of these dew points is given in section 2.2.

3.3.2 Generalized estimates of orographic PMP

One method of applying the model for developing generalized estimates of PMP is to define terrain profiles over the entire region of interest. If the topography is relatively uncomplicated and all general windward slopes face one most critical moisture-inflow direction, as in the California Sierra Nevada, application of this procedure presents no special problems.

An alternative method is to use the model to compute PMP for selected terrain profiles and to evaluate PMP between them by means of maps, such as seasonal or precipitation-frequency maps, adequately depicting the geographic distribution of precipitation. In this approach it must be shown first that there is good correlation between computed orographic PMP on the selected computation profiles or areas and the values indicated by reference maps used for interpolation.

A somewhat different approach has been used [10] for regions where the optimum moisture-inflow direction and orientation of slopes varied from place to place. The procedure consists of computing PMP for terrain profiles oriented in different directions and then enveloping the greatest values regardless of inflow direction or slope orientation. Relations are then developed for adapting the envelope values to inflow directions and slope orientations critical for a specific basin. A simple but adequate method for making such adaptations is to use a variation with basin size, since the variety of optimum inflow directions and slope orientations tends to increase with size of area. This type of adjustment was used in a study for the north-western United States [10]. In the California study [8], the adjustment was based on the decrease of moisture with increasing width, or lateral extent, of inflow in observed major orographic storms (section 3.3.3.3).

Generalized estimates of PMP are usually presented on an index map showing isohyets of PMP for a particular duration, size of area, and month. Relations are then provided for adjusting the mapped PMP values to other durations, basin sizes, and months.

Figure 3.9 shows the January 6-hour orographic PMP index map developed in the aforementioned California study. This particular map does not specify an area size. In this case, the average index value for any specified basin is obtained by laying an outline of the basin on the index map and then estimating the average of the values within the outline. No further areal adjustment is required unless the width of the basin exposed or normal to the optimum moisture inflow exceeds 50 km (section 3.3.3.3).

3.3.3 Variations in orographic PMP

As mentioned above, PMP varies with region, season, duration, and size of area. The generalized maps show the regional variation, and no further discussion is required. While the discussion of the other variations presented in this section applies particularly to the orographic separation method, especially as used in the California study given as an example, much of it applies to variations of orographic PMP in general.

3.3.3.1 Seasonal variation

In any region where snowmelt is likely to contribute significantly to the probable maximum flood, it is necessary to determine the seasonal variation of PMP. In orographic regions the seasonal variation should be determined even when snowmelt is not involved in order to insure that the month of highest potential for total PMP (orographic plus convergence) has not been overlooked. A logical procedure is to compute PMP for each month on the basis of maximum values of wind and moisture in each month. The seasonal variation of major storms recorded over a long period is generally a useful guide in delineating the seasonal variation of PMP.

Evaluation of orographic PMP by means of the model has several shortcomings. In the transitional seasons (spring and autumn), the usual orographic influences prevail, but stimulation of storm precipitation by upwind slopes or barriers is often most effective in determining precipitation distribution. The need for generalizing topography leads to differences between computed orographic PMP and that indicated by the actual terrain. For different terrain profiles, seasonal influences may vary with barrier height, steepness of slope, and other features. In some cases, a compromise between seasonal variation indicated by computed PMP values and that based on maximum storm rainfall amounts observed at well-exposed stations may yield the most realistic results.

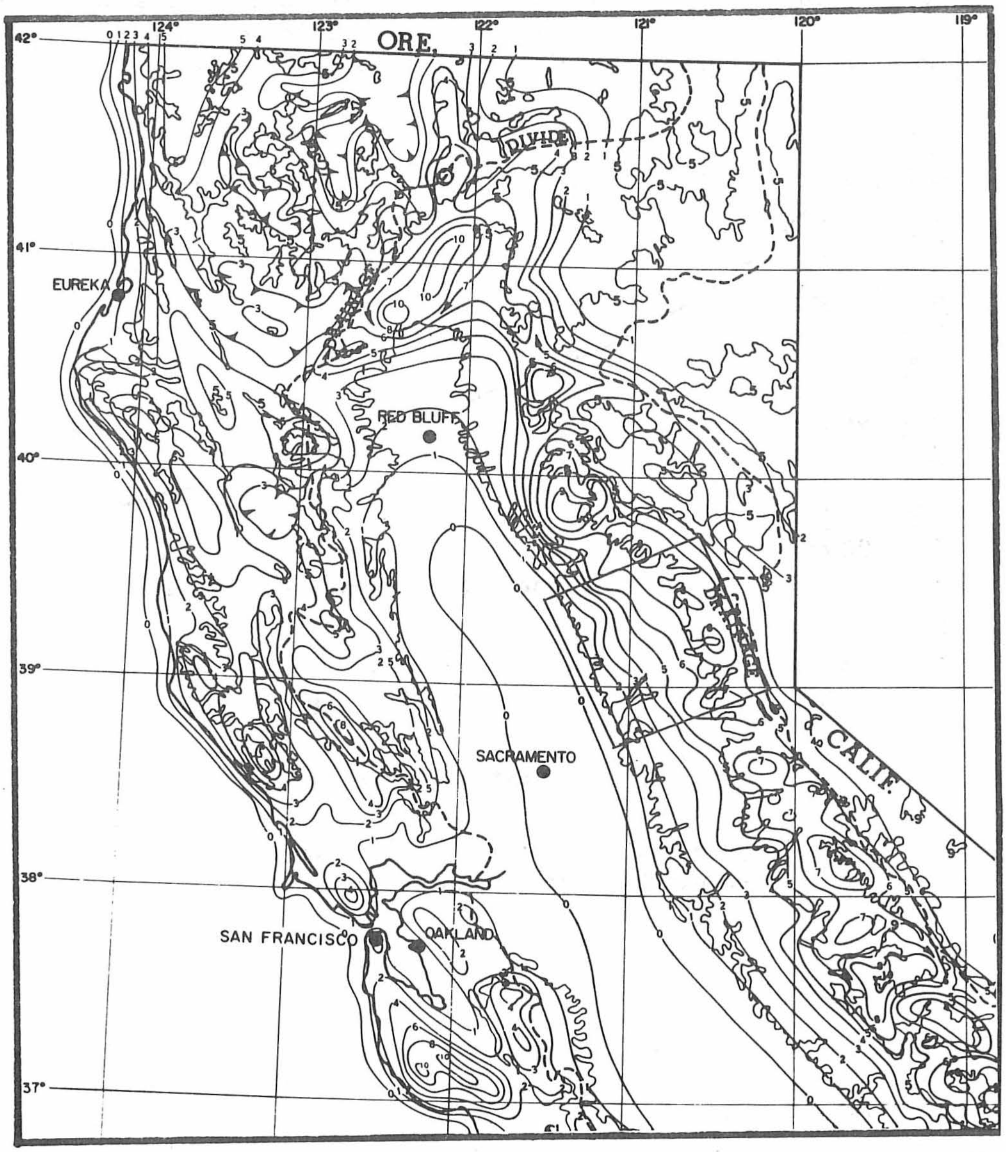

Figure 3.9 - Six-hour orographic PMP (in) for January. (Square delineates Blue Canyon orographic model test area)

3.3.3.2 Durational variation

Variations in maximum wind speeds and moisture with time are used to determine durational variation of computed orographic PMP. The variation of winds in major observed storms is probably the best type of information to use in establishing variations in the shape of the inflow profile with duration, and this was used in the example study. Variation of moisture with time was based on the durational variation of maximum persisting 12-hour 1 000 mb dew points /7/. Moisture values at upper levels were based on the assumption of a saturated pseudo-adiabatic lapse rate. A common durational variation (Figure 3.10) for all months and regions was adequate for the example study. An additional factor found helpful in some studies /10/ is the variation of moisture with duration during major observed storms.

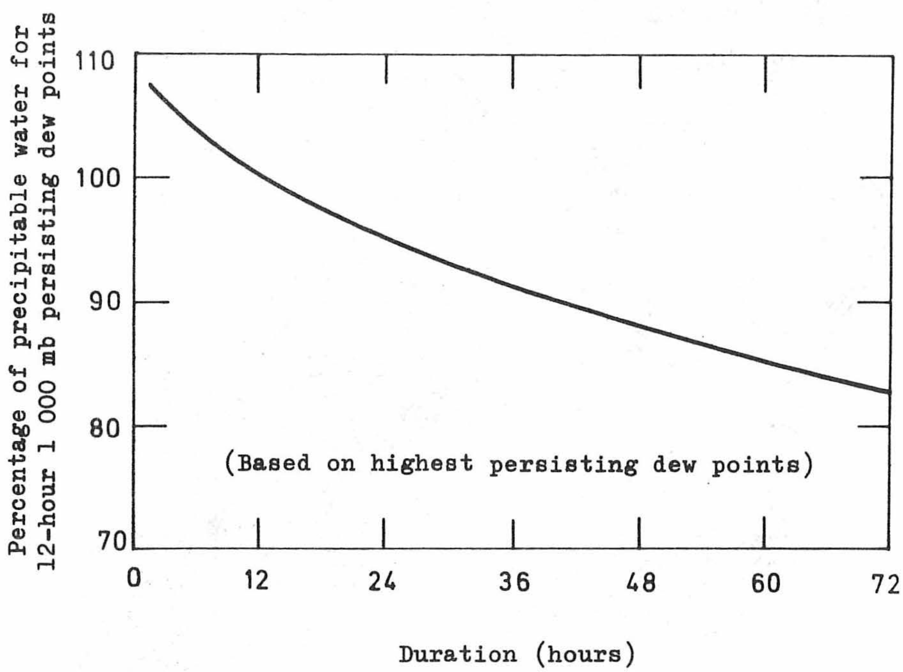

Figure 3.10 - Decrease of maximum precipitable water with duration

3.3.3.3 Areal variation

The variation of orographic PMP with basin size is controlled by the orography, and therefore may vary greatly from basin to basin. As stated in section 3.3.2, the averaging of index PMP by superimposing an outline of the basin on the index map eliminates the need for the usual type of depth-area relation. The average index PMP thus obtained usually requires some adjustment for basin size, however, since the intensity of moisture inflow decreases with increasing width of inflow. In the example study /8/ no adjustment was required for basin widths up to 50 km, but a reduction curve for greater widths reduced the basin average index PMP by 15 and 25 per cent for widths of 160 and 300 km, respectively.

3.3.4 Convergence PMP for combination with orographic PMP

The procedure described here for estimating convergence (non-orographic) PMP for combination with orographic PMP was developed for the coastal regions of California [8], where the critical season for major orographic storms is October to March. The approach, which has been used elsewhere, is basically similar to those used in estimating PMP for non-orographic regions. The greatest precipitation amounts for various durations at stations in the least orographically influenced areas are maximized for moisture. This is done in two steps. First, regional envelopes of maximum persisting 12-hour 1 000 mb dew points are determined for use in evaluating maximum moisture, M, or precipitable water, W. Second, durational envelopes of maximum P/M ratios at each station are determined for each month. Here, P is the storm precipitation for a particular duration; and M, the precipitable water for the representative persisting 12-hour 1 000 mb storm dew point (section 2.2.4).

P/M ratios should be computed for several of the highest rainfalls at any particular station because the maximum rainfall does not necessarily yield the highest P/M ratio. Maps of maximum moisture and P/M ratios are then drawn. Multiplication of corresponding values from appropriate pairs of maps yields moisture-maximized rainfall amounts for any required location, or $(P/M)_{max}$ multiplied by M_{max} equals convergence PMP.

3.3.4.1 Moisture (dew point) envelopes

Maximum, or 100-year, persisting 12-hour 1 000 mb dew points (section 2.2.5), enveloped seasonally at each station (Figure 3.11) and smoothed regionally (Figure 3.12) are used to establish the level of maximum moisture available for evaluating convergence PMP. In the example study [8], one mean seasonal variation curve (not shown) was found applicable to the entire region of interest. Different seasonal trends for different portions of a region would increase only the details of application.

3.3.4.2 Envelopes of P/M ratios

Finding suitable station precipitation data uninfluenced by orography is a problem. In the example study, the search was confined to the large flat valley between the coastal mountains to the west and the Sierra Nevada to the east, and to some coastal stations unaffected by nearby steep slopes. Except for a few short intense rainfalls, most data were observational-day or highest 24 consecutive 1-hour amounts. Envelope curves of highest P/M ratios found in the restricted region are shown in Figure 3.13.

Adequate data on intense rainfalls for establishing a seasonal trend in P/M ratios would have been desirable, but there were not enough of these data in the problem area. However, many plots of maximum 24-hour precipitation at non-orographic stations indicated no definite seasonal trend for any magnitude. On the other hand, such trends did exist for 6- and 72-hour precipitation (Figure 3.14).

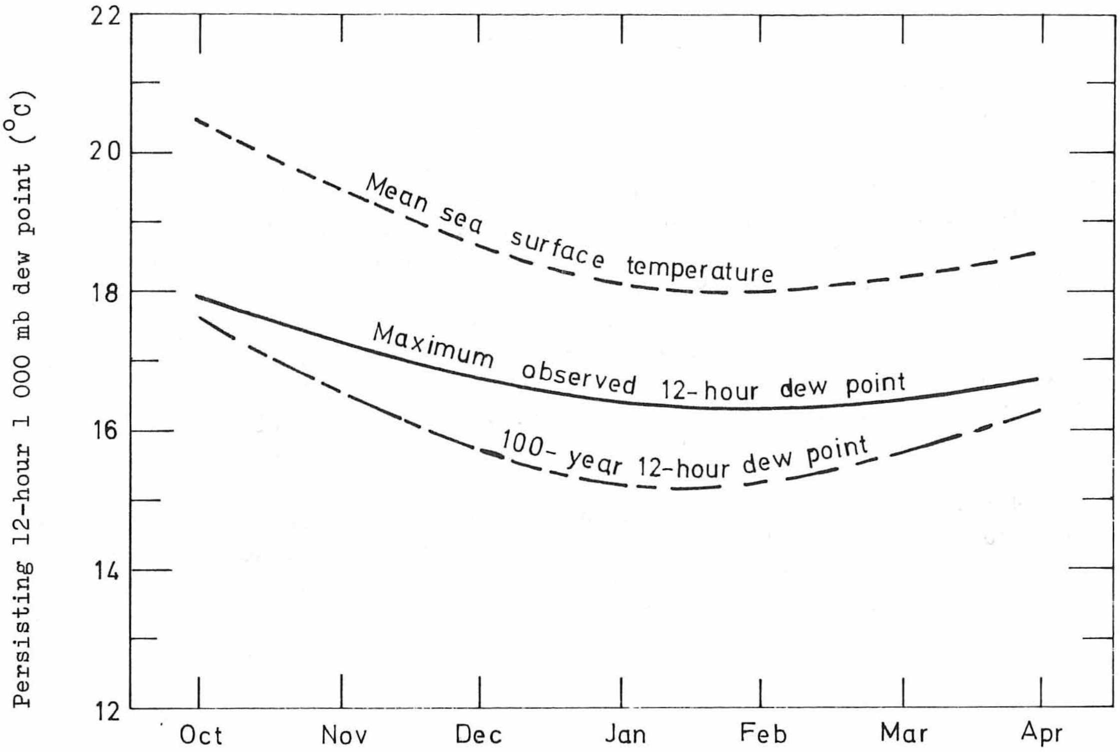

Figure 3.11 - Seasonal envelope of maximum observed dew points at Los Angeles, California

It was concluded that seasonal trends of moisture and P/M ratios for the 24-hour duration must counteract each other since there was no trend in 24-hour precipitation. On the basis of this concept, the greatest 24-hour P/M ratio was assigned to February, the month having the lowest maximum precipitable water; and ratios for other months were evaluated in proportion to their maximum precipitable water, as indicated by their maximum persisting 12-hour dew points.

The ratios of 6- to 24-hour and 72- to 24-hour precipitation (Figure 3.14) were used to establish P/M ratios for 6 and 72 hours. This was possible since 12-hour moisture, the denominator M in the ratios, was used for all durations. The durational variation of P/M ratios is thus the same as the durational variation in precipitation, P. Monthly curves of durational variation of P/M ratios are shown in Figure 3.13.

3.3.4.3 Reduction of convergence PMP for elevation

In the example study /8/, PMP values computed as described in the first two paragraphs of section 3.3.4 were reduced for elevation. For gently rising slopes where storm precipitation was apparently little affected by upwind barriers, the decrease in convergence PMP was assumed to be proportional to the decrease of precipitable water, W, in a saturated column of air. This decrease was computed as the difference between W in a column with base at the ground elevation at a point 8 km upwind

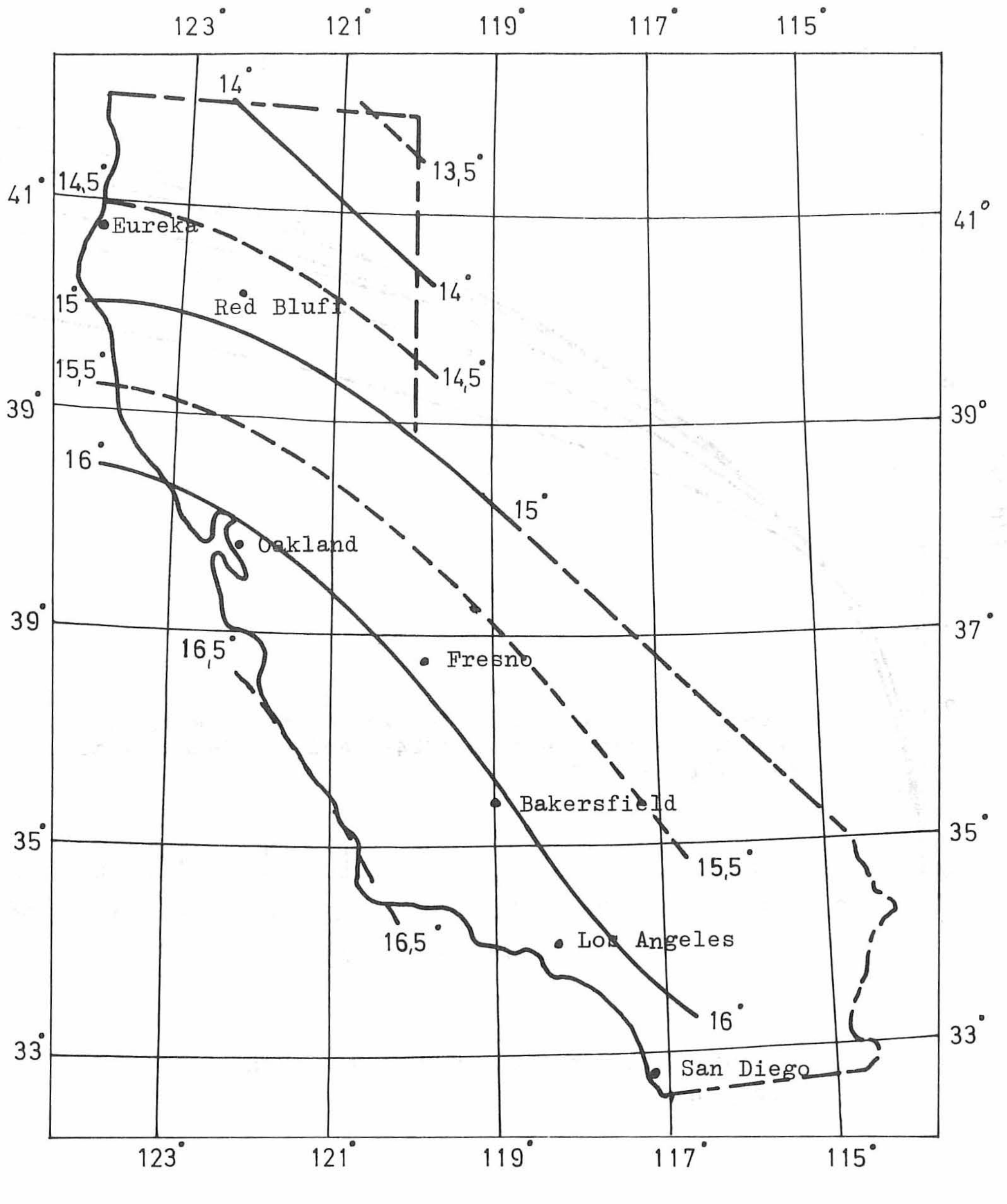

Figure 3.12 - Maximum persisting 12-hour
1 000 mb dew points (°C) for February

from the problem area and that with base at the ground elevation of the convergence PMP. The 8 km distance upwind marks the average location of the formation of the storm precipitation particles falling on the problem area.

In estimating PMP by methods other than the orographic separation method, the usual procedure is to base the decrease on the difference between observed storm amounts on slopes and in valleys. In one study [10], the non-orographic, or convergence, PMP was reduced by 5 per cent for every 300 m increase in elevation.

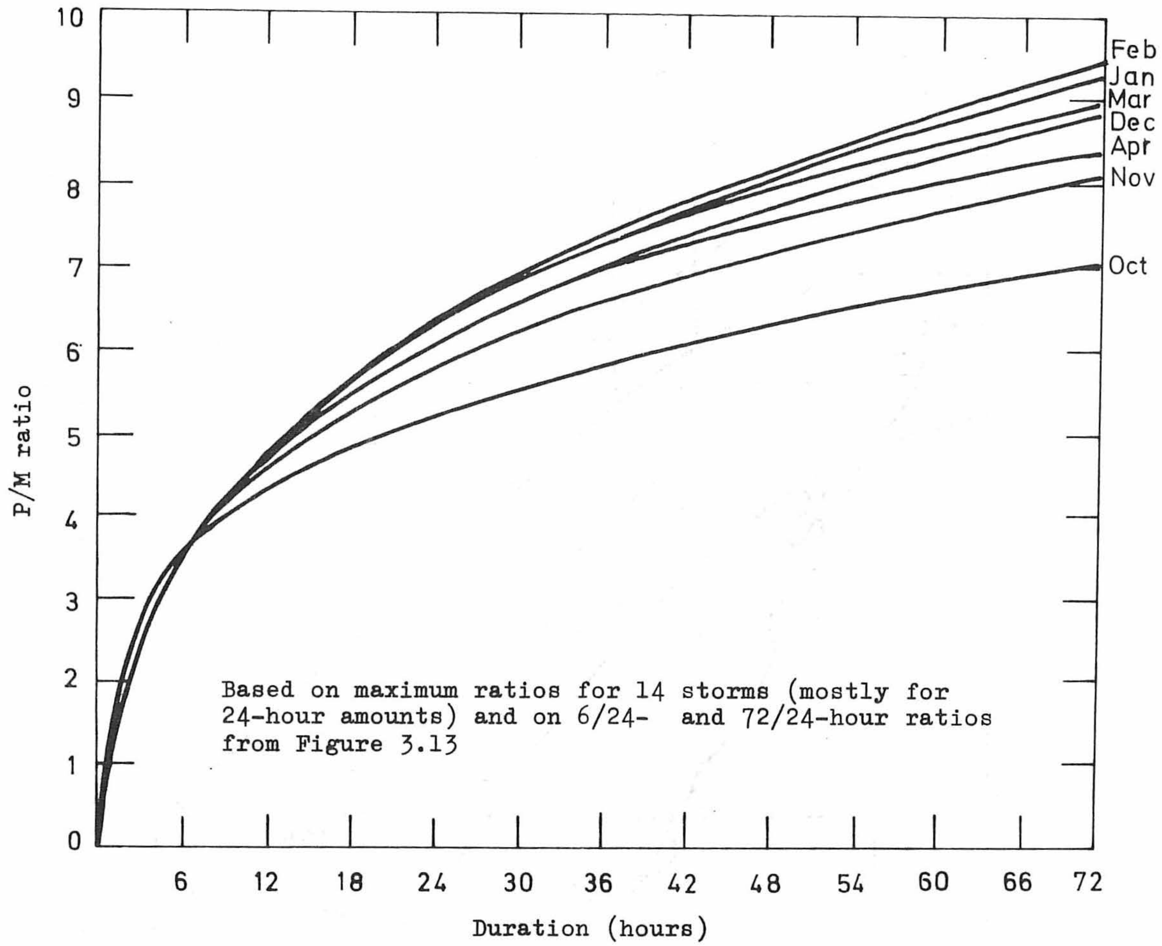

Figure 3.13 - Maximum P/M ratios with orographic storms

3.3.4.4 Reduction for upwind barriers

The amount of moisture that a column of air can contain is obviously reduced by a shortening of the column as it crosses an orographic barrier. Convergence PMP is therefore adjusted for the moisture depletion by upwind barriers. In making the reductions, so-called effective barrier heights are used rather than actual heights. Maps of effective barrier heights (Figure 3.15) differ from actual topographic maps in that they take into account the effect of barriers on air crossing them. Also, since the maps are intended for use in making generalized estimates of PMP, effective barrier height contours naturally smooth out the smaller irregularities in crest height, ridge orientation, and other orographic features. Local features that would seriously affect precipitation over small basins are thus smoothed out.

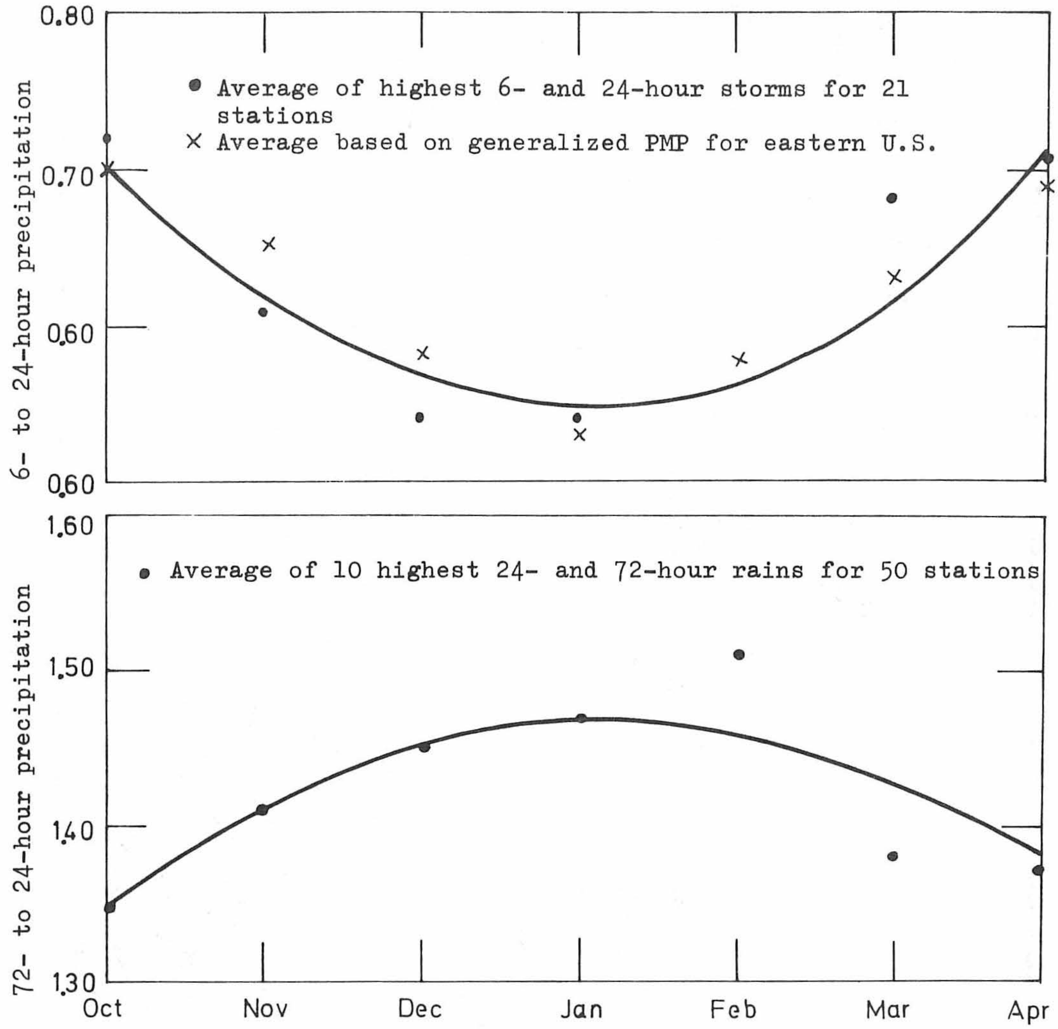

Figure 3.14 - Ratios of 6- and 72-hour precipitation to 24-hour precipitation

3.3.4.5 Reduction of point, or 25 km^2, convergence PMP for basin size

Point precipitation data (arbitrarily accepted as representative for 25 km^2) were used in the derivation of convergence PMP described above. Ideally, the 25 km^2 values would be reduced for basin size by depth-area relations based on observed storms that produced heavy convergence (non-orographic) rainfalls in the problem area. Sparsity of storm-centred data in non-orographic areas in the region of interest, however, precluded the development of such relations. It was therefore necessary to develop depth-area relations for extreme storms (excluding tropical storms) in regions where orography had little or no influence on storm precipitation.

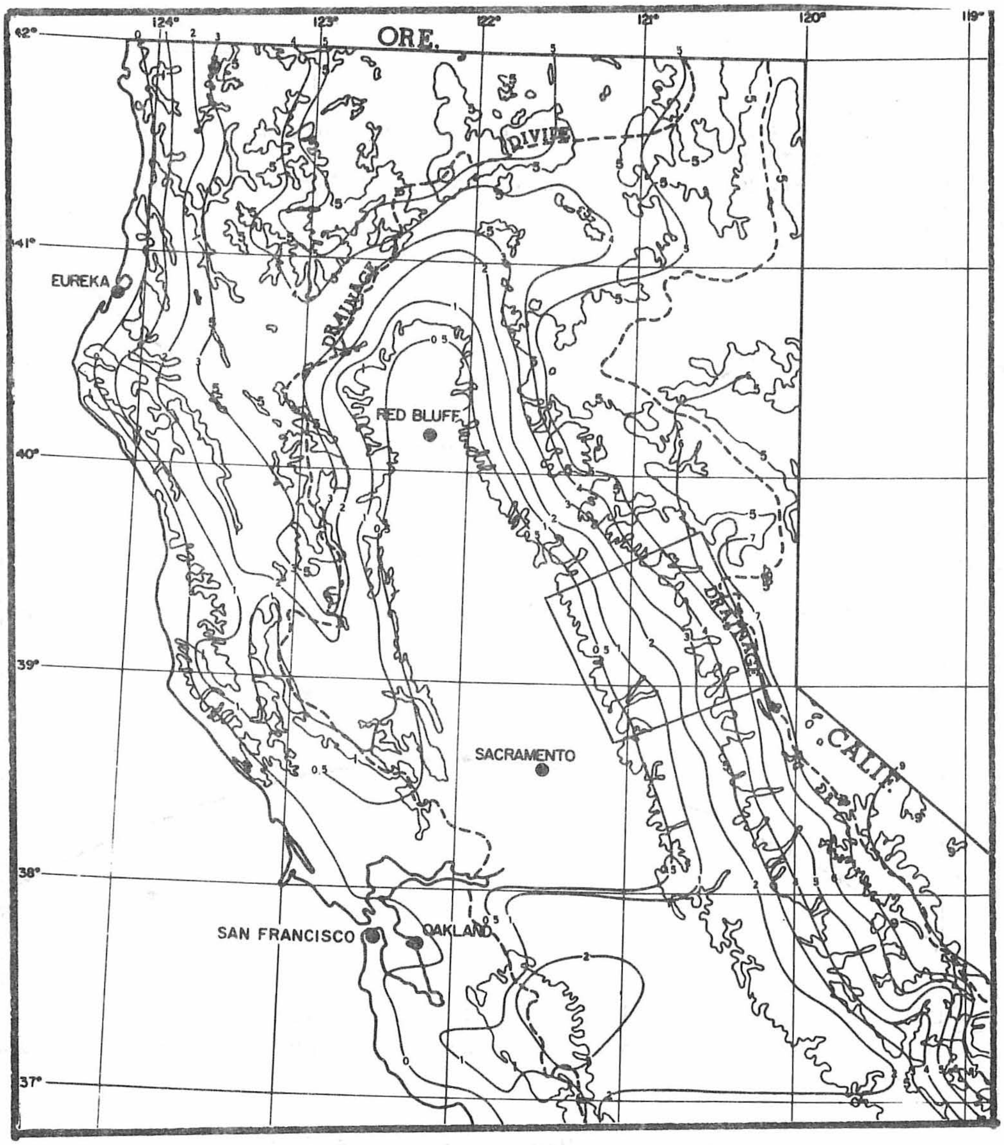

Figure 3.15 - Effective elevation and barrier heights (1 000 ft) in northern California. (Square delineates Blue Canyon orographic model test area)

3.3.4.6 Construction of convergence PMP index map

The steps described below for the construction of the six-hour 500 km^2 convergence PMP index map (Figure 3.16) for February in the example study apply equally well to similar index maps for other durations, basin sizes and months if required.

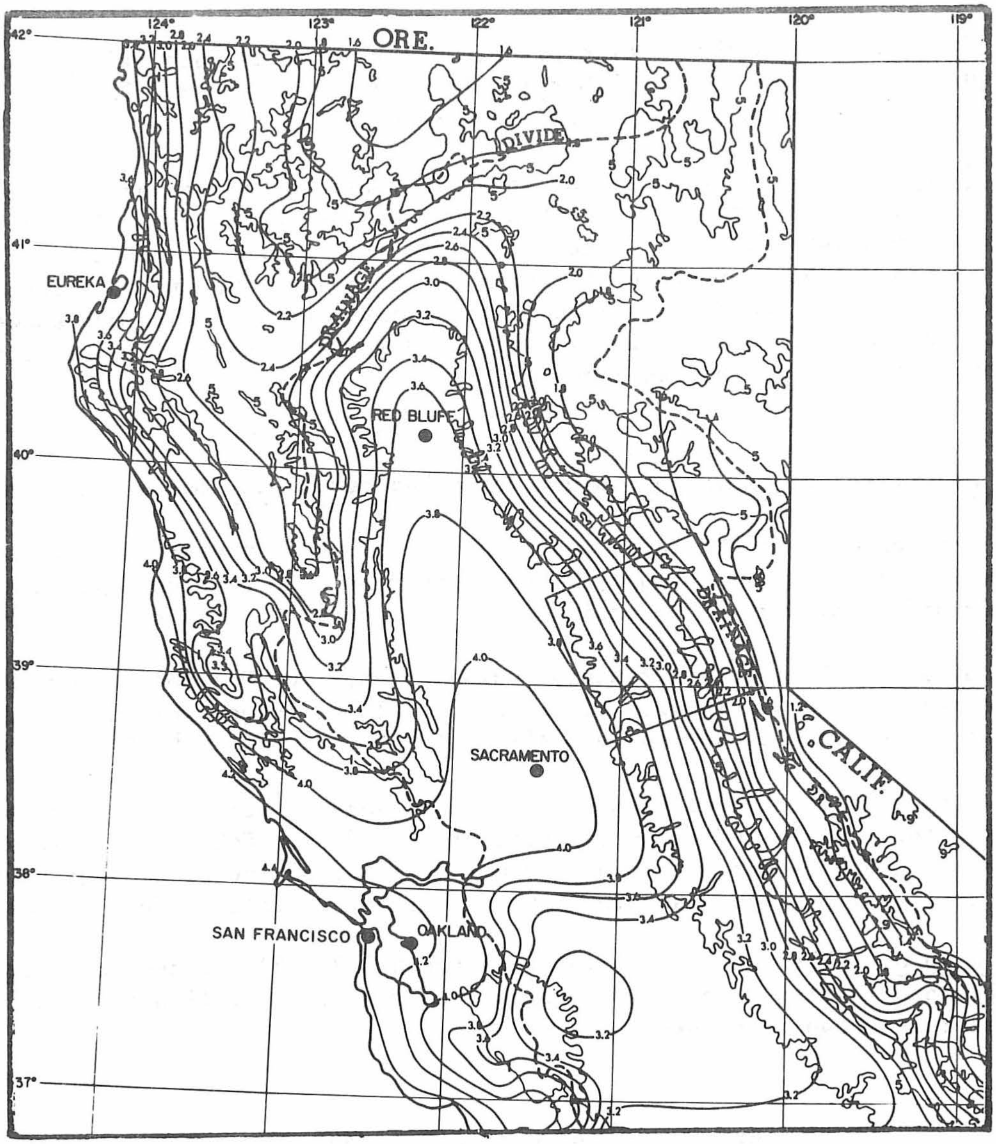

Figure 3.16 - Six-hour 500 km^2 convergence PMP (in) for January and February. (Square delineates Blue Canyon orographic model test area)

Step 1. After an appropriate grid had been drawn on a suitable map base, the maximum moisture for February was determined for each grid point and plotted thereon. These maximum moisture (precipitable water) values were first obtained from the maximum persisting 12-hour 1 000 mb dew points for February (Figure 3.12), and then adjusted for effective elevation or barrier height (Figure 3.15).

Step 2. The adjusted precipitable water value at each grid point was then multiplied by the maximum 6-hour P/M ratio for February (Figure 3.13). The values thus multiplied represent 6-hour 25 km^2 convergence PMP.

Step 3. The convergence PMP values computed as above were then adapted to 500 km^2 by a reduction factor (0.80) obtained from the depth-area relation (not shown) described in paragraph 3.3.4.5. Isopleths were then drawn on the basis of these areally reduced values to produce the index map of 6-hour 500 km^2 convergence PMP shown in Figure 3.16. The factors involved in the construction of this map showed little difference in January, so the index map was used without seasonal adjustment for both January and February, and was so labelled.

3.3.4.7 Adjustment of index map values for other durations, basin sizes and months

The convergence PMP index map, constructed as just described, presents 6-hour 500 km^2 values for January-February. Relationships were developed for adjusting these values for different durations, basin sizes, and months. This was done as follows:

Step 1. Six-hour incremental values of maximum P/M ratios through 72 hours were obtained for each month from Figure 3.13. These values were smoothed and expressed as percentages of the maximum six-hour P/M ratio for February.

Step 2. Durational (Figure 3.10) and seasonal variations of moisture (precipitable water), expressed as percentages of the 12-hour February moisture (based on maximum persisting 12-hour dew points) and multiplied by the percentage variation in P/M ratios (Step 1), yielded seasonal and durational variations for a point, or 25 km^2.

Step 3. The areal variation (paragraph 3.3.4.5) was then applied to the values obtained in Step 2 to yield a depth-area-duration relation for each month. That for December is shown in Figure 3.17.

3.3.5 Combination of orographic and convergence PMP

Total PMP is obtained by adding the orographic and convergence components. Throughout the development of each component, care must be exercised to minimize the possibility of over-estimating total PMP. In computing orographic PMP, for example, the model should be tested against observed orographic precipitation only. Testing may be restricted to storm periods showing little or no evidence of convergence precipitation, or the convergence component of total observed precipitation may be estimated (section 3.2.3.7) and subtracted from the total to obtain an estimate of the orographic component.

In estimating convergence PMP, the measure of the storm mechanism, or efficiency, is the P/M ratio computed from outstanding storms. As a precaution against over-maximizing, only P/M ratios from general-type storms producing heavy orographic precipitation should be used. Another precaution is to use only maximum persisting 12-hour dew points observed in major general-type storms for moisture maximization.

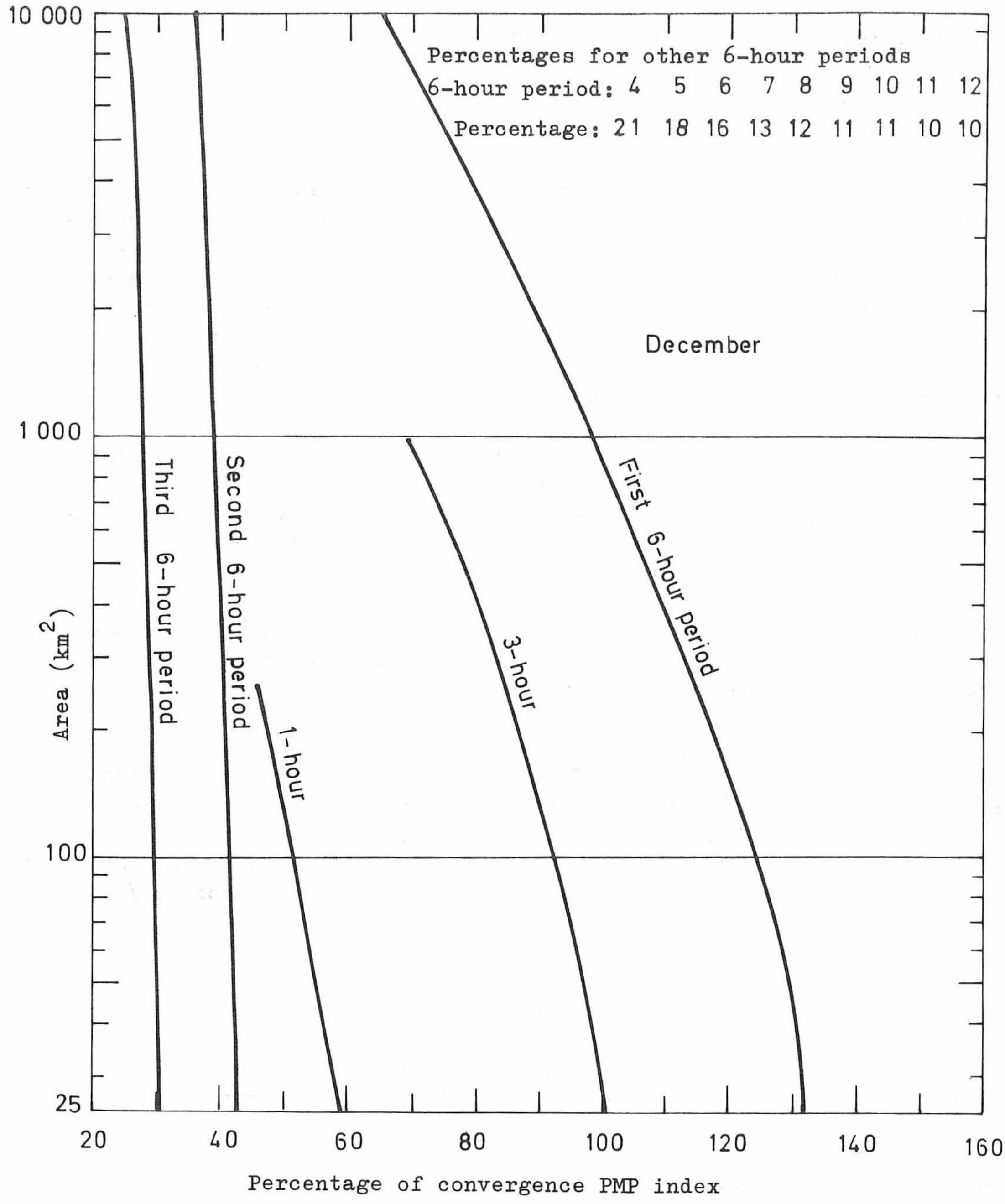

Figure 3.17 - Variation of convergence PMP index with basin size and duration for December

3.4 Modification of non-orographic PMP for orography

3.4.1 Introduction

Two general approaches for estimating PMP in orographic regions were briefly mentioned in section 3.1.5. One, the orographic separation method, was described in detail in section 3.3. The other, as the title of this section implies, consists of first estimating the non-orographic PMP for the mountainous problem region and then applying modifying factors for adjusting the non-orographic PMP for orographic effects. The non-orographic PMP may be determined for the plains area in the region of interest, or, if there are no broad plains areas, it may be estimated as if the mountains did not exist in order to provide a working base.

While modification of non-orographic PMP is used more often than the orographic separation method, it is being described in less detail because descriptions have been published in reports on studies made for the Hawaiian Islands [3], Tennessee river basin [4, 5], and Mekong river basin [11]. The orographic separation method could not be used in these three problem areas for the reasons cited below.

In the Hawaiian Islands, relatively isolated peaks or short ridges are relatively ineffective in lifting moist air as required by the orographic model. Observations indicate that streamlines are diverted horizontally in such terrain.

The Tennessee river basin includes multiple ridges at various angles to moisture inflow directions. Critical inflow directions vary from south-west to south-east. Moisture inflow from any direction in this range can produce heavy rainfalls in some portion of the basin. Another obstacle to the use of the orographic model here is the relatively large variability of storm wind direction with height, so simple wind profiles, as used effectively for the Sierra Nevada slopes in California [8], are not appropriate.

The orographic model could not be used for the Mekong river basin for several reasons. In regions near the tropics, precipitation variation with topography is different from that in middle latitudes. Atmospheric moisture is near saturation levels, and first slopes are important in setting the locations for heavy rains. Also, atmospheric instability is generally greater. Laminar wind-flow across mountain barriers, which results in heaviest rainfalls near the highest elevations, is not supported by observations. Another obstacle is that typhoons, which set the level of PMP for durations up to three days, show no simple relation between wind speed and rainfall, so that maximization for wind is difficult.

Modification of non-orographic PMP for orography as used in a study for the Tennessee river basin above Chattanooga, Tennessee [4], is described below. The procedure as used in generalized estimates of PMP for the Hawaiian Islands [3], Tennessee river basin [5], Mekong river basin [11] in south-east Asia, and for thunderstorm rainfall in the Columbia river basin in north-western United States [10] is described in Chapter 5.

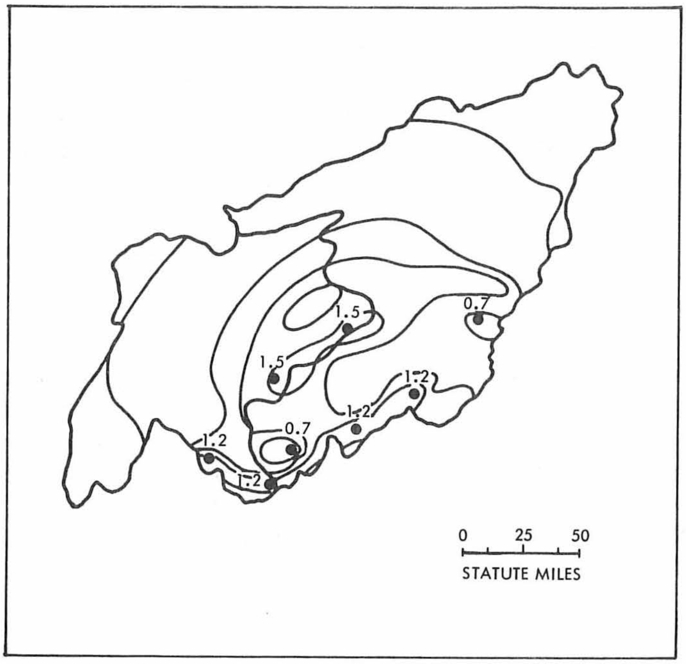

Figure 3.18 - Typical orographic rainfall pattern for south-westerly winds. Isolines indicate ratios of orographic to non-orographic rainfall

3.4.2 Tennessee river basin above Chattanooga, Tennessee

A study [4] for the Tennessee river basin covered the 55 000 km^2 area above Chattanooga, Tennessee, and a 21 000 km^2 sub-basin in the lower portion just above Chattanooga. Topography of the larger basin varies from the rugged mountains of the south-eastern portion with peaks above 1 500 m to a relatively smooth central valley extending from south-west to north-east. North-west of the valley lies a series of parallel ridges extending from south-west to north-east with peaks to about 1 000 m. Chief moisture sources are the Gulf of Mexico about 600 km to the south, and the Atlantic Ocean about 500 km to the south-east. A typical orographic rainfall pattern for south-westerly winds is shown in Figure 3.18. The values shown are ratios of orographic to non-orographic precipitation as estimated from a study of several major storms.

The approach described below is the one used for estimating PMP for these two basins. Other approaches could have been used with equally valid results.

3.4.2.1 Topographic effects

A major consideration in assessing topographic effects was whether they would produce a net increase or decrease of average basin PMP as compared to that to be expected if there were no mountains. Increases, of course, would be related to slopes exposed to moisture inflow, while decreases would be associated with sheltered, or lee, areas, but what would the net effect be on the basin as a whole?

Mean annual precipitation was used first as basis for comparison. Observed basin average precipitation indicated a net basin-wide increase of about 10 per cent above estimates for surrounding non-orographic areas.

February, March and August were selected for estimating topographic effects on monthly rainfall volume. The larger basin was divided into three zones (Figure 3.19): (A) a zone of minimal topographic effects, (B) an orographic depletion zone, and (C) an orographic intensification zone. The average precipitation in zone A was used as a base. The mean precipitation for each of the 3 months indicated a net topographic depletion for the winter months based on the zone B decrease overcompensating for the orographic zone C increase.

A similar comparison based on the mean of seven unusually wet months selected from the January-April season in six different years showed no appreciable difference between precipitation in depletion zone B and that in intensification zone C.

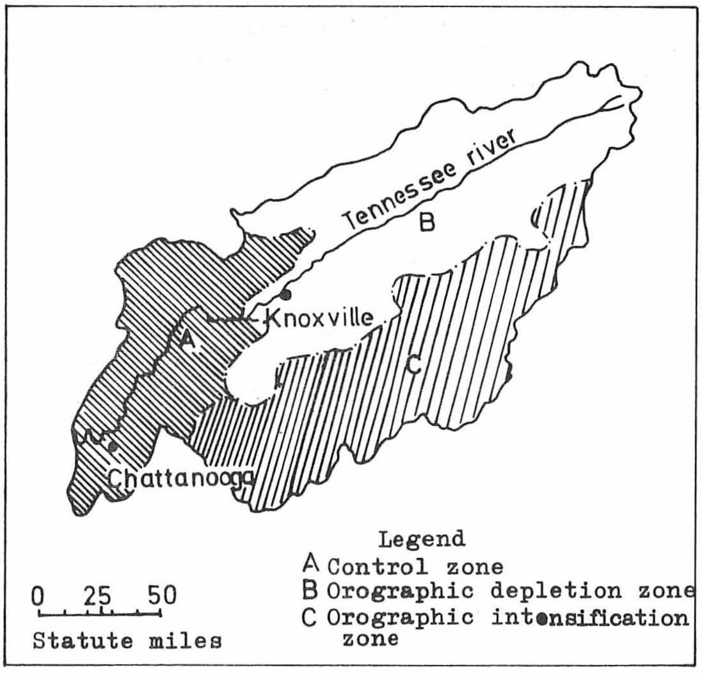

Figure 3.19 – Basin subdivisions for check of topographic effects on basin-wide precipitation volume

Daily station rainfalls averaged over the Tennessee river basin above and below Chattanooga were used as an auxiliary indicator of net orographic effects. The area above Chattanooga can be likened topographically to zones B and C, and the area below, to zone A (Figure 3.19). Comparison of the means of the series of monthly maximum daily averages showed a net deficit for the basin above Chattanooga.

Although mean annual precipitation indicated a modest orographic intensification, the more extreme precipitation data tended to negate such intensification. The net effects, if any, are apparently small, and it was assumed that there was no net topographic effect on the volume of precipitation for the basin as a whole.

3.4.2.2 Derivation of PMP

About three dozen major storms scattered throughout the eastern half of the country were maximized, and generalized charts of PMP were prepared for south-eastern United States. It developed that March storms provided controlling PMP values for the basins, and a map of 24-hour 25 000 km^2 March PMP was drawn (Figure 3.20). The PMP value for the centre of the 21 000 km^2 sub-basin was then read from this map, and adjusted upward slightly, on the basis of depth-area relations of observed storms, for the difference in area size. The 24-hour March PMP for the sub-basin was thus determined to be 357 mm.

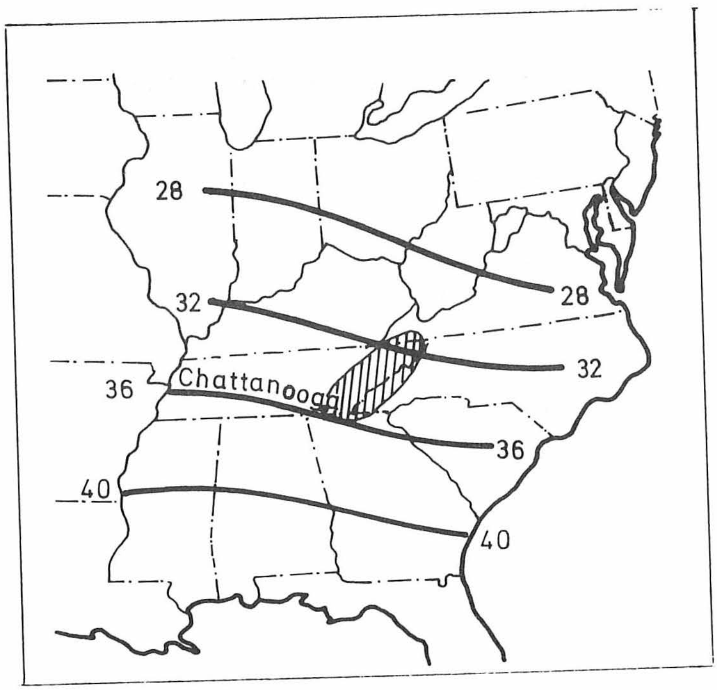

Figure 3.20 - March 24-hour 25 000 km^2 PMP (cm)

3.4.2.3 Seasonal variation

Study of outstanding storms of the region indicated that, for the basin sizes involved, a March storm would be more likely to produce PMP than would summer tropical storms. Tropical storms, which usually occur with near-maximum dew points, were adjusted to the basin location on the basis of decreased rainfall with distance inland of observed storms. Other precipitation data, such as wettest seven-day periods and months, rainfall-frequency data, and some unpublished generalized PMP estimates for 50 000 km^2, were used in setting the seasonal variation for the larger basin. The seasonal variation was first determined for the larger basin, because of previous studies for that size of area, and applied to the sub-basin as described below. Figure 3.21 shows the adopted seasonal variation of PMP for the 55 000 km^2 basin as a percentage of March PMP.

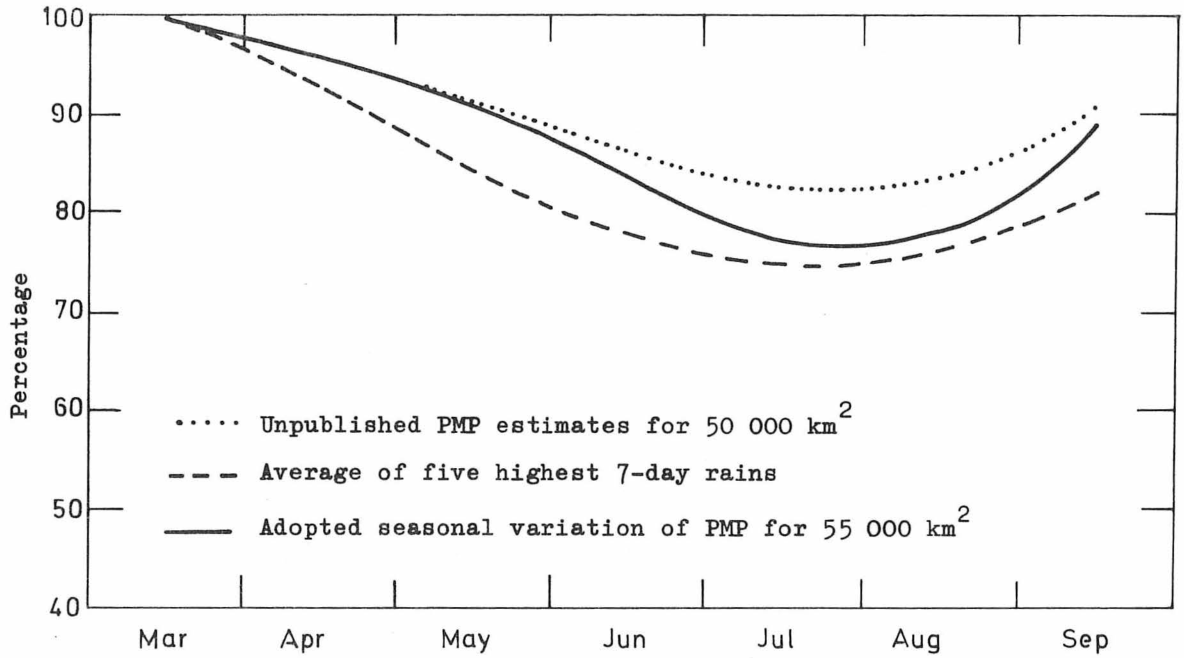

Figure 3.21 - Seasonal variation of PMP for 55 000 km^2 as percentage of March PMP

A seasonal variation curve of the ratio of 24-hour storm rainfall for 55 000 km^2 to that for 21 000 km^2, the areas of the two project basins, was based on some two dozen major storms in the south-eastern part of the country. This ratio curve (Figure 3.22) was used to estimate PMP for the larger basin from that for the smaller, with an additional reduction of about 2 per cent for the north-eastward displacement of the centre of the large basin. This small adjustment was based on PMP values indicated by Figure 3.20. Application of the basin centre adjustment and area ratio for March to the sub-basin PMP (357 mm) yielded a 24-hour March PMP of 284 mm for the larger basin.

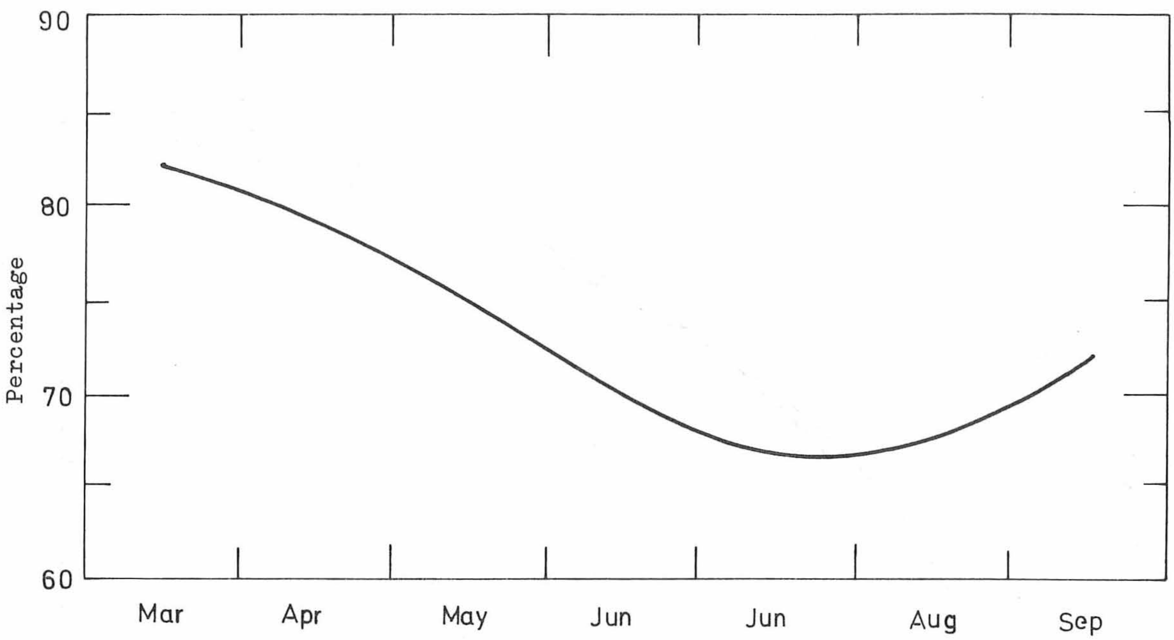

Figure 3.22 - Depth-area ratios ($55\ 000/21\ 000\ km^2$) for 24-hour rainfall

The seasonal variation curve of Figure 3.21 was then applied to the 24-hour March PMP for the larger basin to obtain 24-hour PMP for April to September as shown on line 5 of Table 3.4. These PMP values were then adjusted for area by the reciprocal of the ratio curve of Figure 3.22 to yield April to September 24-hour PMP for the sub-basin (line 2, Table 3.4).

3.4.2.4 Depth-duration relations

Depth-duration relations, particularly 6/24- and 72/24-hour ratios, of over 100 outstanding storms in the eastern part of the country were examined. Although the storms occurred in various months during the March-July period, no seasonal trend was indicated. The adopted depth-duration curves (Figure 3.23) show slight differences for basin size. These curves were used to adjust 24-hour PMP values of Table 3.4 to 6- and 72-hour amounts.

3.4.2.5 Geographic distribution of PMP

It was stated earlier that there was no net decrease or increase of basin rainfall as compared to surrounding areas. This does not mean that there are no topographic effects. Any examination of a number of storms shows that the distribution is definitely affected by the topography. In rugged terrain, topographic effects result in more or less distinct storm rainfall patterns, with appreciable differences between patterns attributable chiefly to wind direction and storm movement.

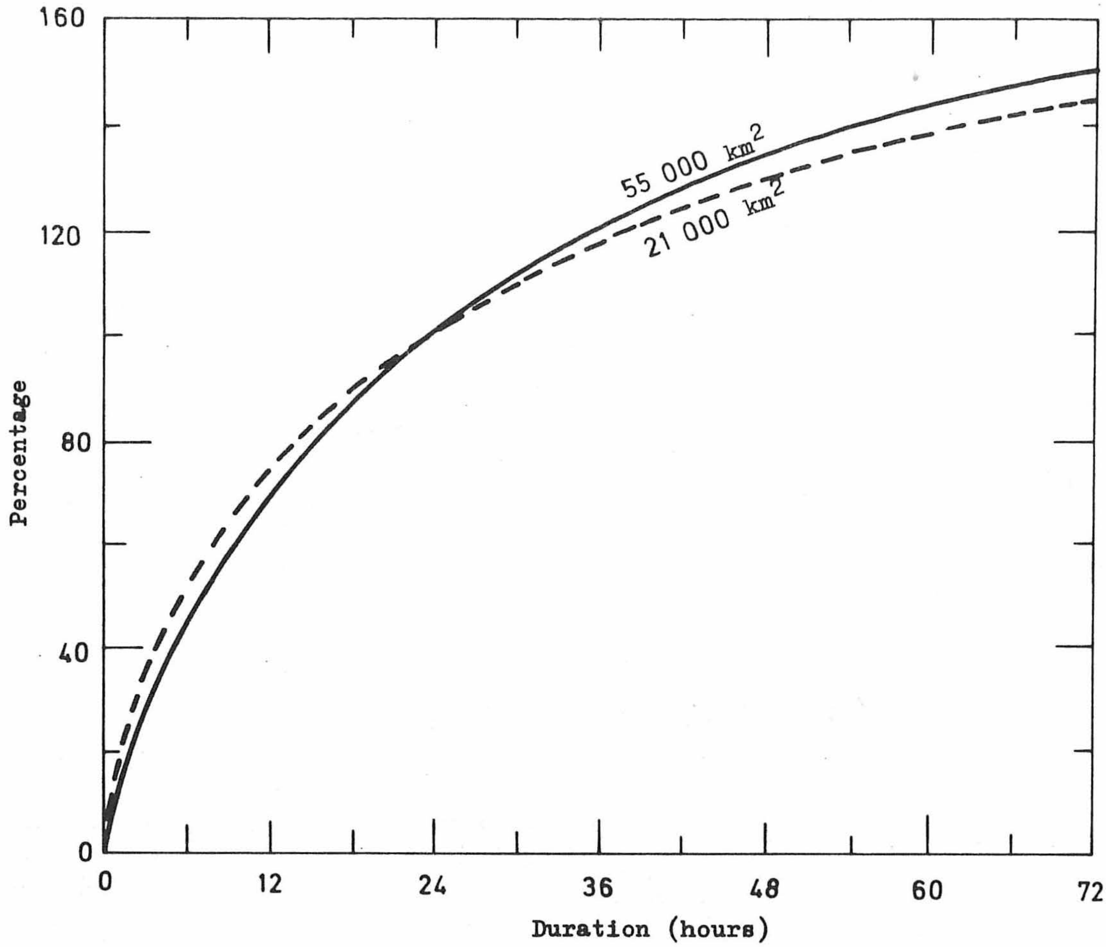

Figure 3.23 - Depth-duration relations in per cent of 24-hour rainfall

The PMP values of Table 3.4 merely represent average depths of basin PMP, and provide limiting rainfall volumes for various possible PMP storm patterns. Examination of isohyetal patterns for a number of outstanding storms over the project basins, together with streamflow data, indicated several critical patterns for the larger basin. Figure 3.24 presents one of these patterns for the 6-hour March PMP.

In order to minimize the work involved in determining pattern configurations and resulting runoff, any selected pattern is generally considered applicable to all durations, with only the isohyet values changing. Isohyet values for the pattern of Figure 3.24 were obtained by the relation of Figure 3.25, which applies to the maximum, or first, 6-hour PMP increment. Similar relations were developed for other 6-hour increments and for 72 hours. These relations were derived in a manner similar to that described in section 2.11.3, with the so-called within-basin, or typical, depth-area curves, like those of Figure 2.14, patterned after outstanding storms in, or transposable to, the project basins.

Table 3.4 - Probable maximum precipitation (mm) for Tennessee river basin above Chattanooga, Tennessee

Line no.	Duration (hours)	Mar.	Apr.	May	June	July	Aug.	Sept.
				Sub-basin (21 000 km^2)				
1	6	178	177	174	171	167	167	178
2	24	357	354	349	342	334	334	356
3	72	517	513	506	496	484	484	516
				Total basin (55 000 km^2)				
4	6	128	123	116	107	98	99	114
5	24	284	273	259	239	219	222	253
6	72	426	409	388	358	328	332	379

Isohyet values for the PMP storm pattern of Figure 3.24 are given in Table 3.5. The isohyet values for the maximum, or first, 6-hour PMP storm pattern of Figure 3.24 were obtained as follows. The total area enclosed by each isohyet was obtained by planimetering. The area was then used to enter the nomogram of Figure 3.25 on the ordinate scale. The corresponding ratio of isohyet value to basin PMP was then obtained by laying a straight-edge across the nomogram at the proper ordinate value and reading the ratio below the intersection of the straight-edge and the appropriate basin area curve. This ratio was then applied to the basin PMP to obtain the isohyet value.

Isohyet values for other 6-hour PMP increments were obtained in a similar fashion from similar ratio relations except that the ratios were applied to corresponding 6-hour PMP increments. Thus, for example, the isohyet values for the second 6-hour PMP increment were determined from a corresponding ratio relation, like that of Figure 3.25, and the second 6-hour PMP increment as indicated by the appropriate depth-duration curve from Figure 3.23.

The effect of geographic distribution of rainfall on runoff generally decreases as basin size decreases. The simple oval-shaped pattern of Figure 3.26 was considered appropriate for the sub-basin. Isohyet values were determined as described above.

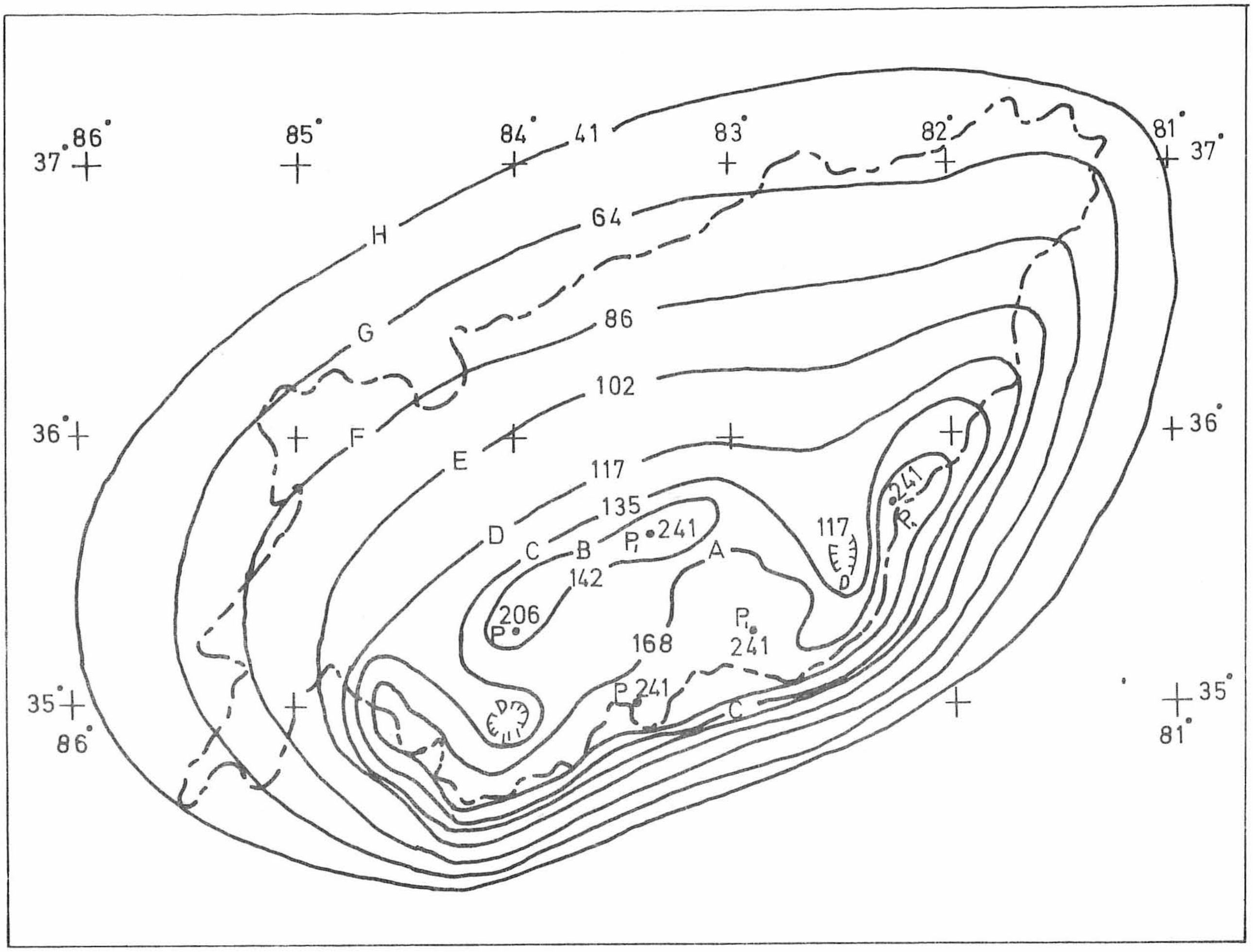

Figure 3.24 - Six-hour March PMP storm pattern (mm) for total basin (55 000 km^2)

3.4.2.6 Time distribution of PMP

The procedures just described yielded 6-hour rainfall incremental values or maps for the 12 periods in the 72-hour PMP storm in any given month in the March-September season. Ranking of first, second, etc., 6-hour increments was based on descending order of magnitude and not on chronological sequence. Storm experience, which provides guidelines for reasonable time sequences, generally indicates a strong tendency for several bursts of rainfall during a 72-hour storm. Within a typical burst, the largest two or three 6-hour increments usually occur in succession. To maintain PMP values for all durations, however, any sequence of n 6-hour increments should consist of the n highest 6-hour values.

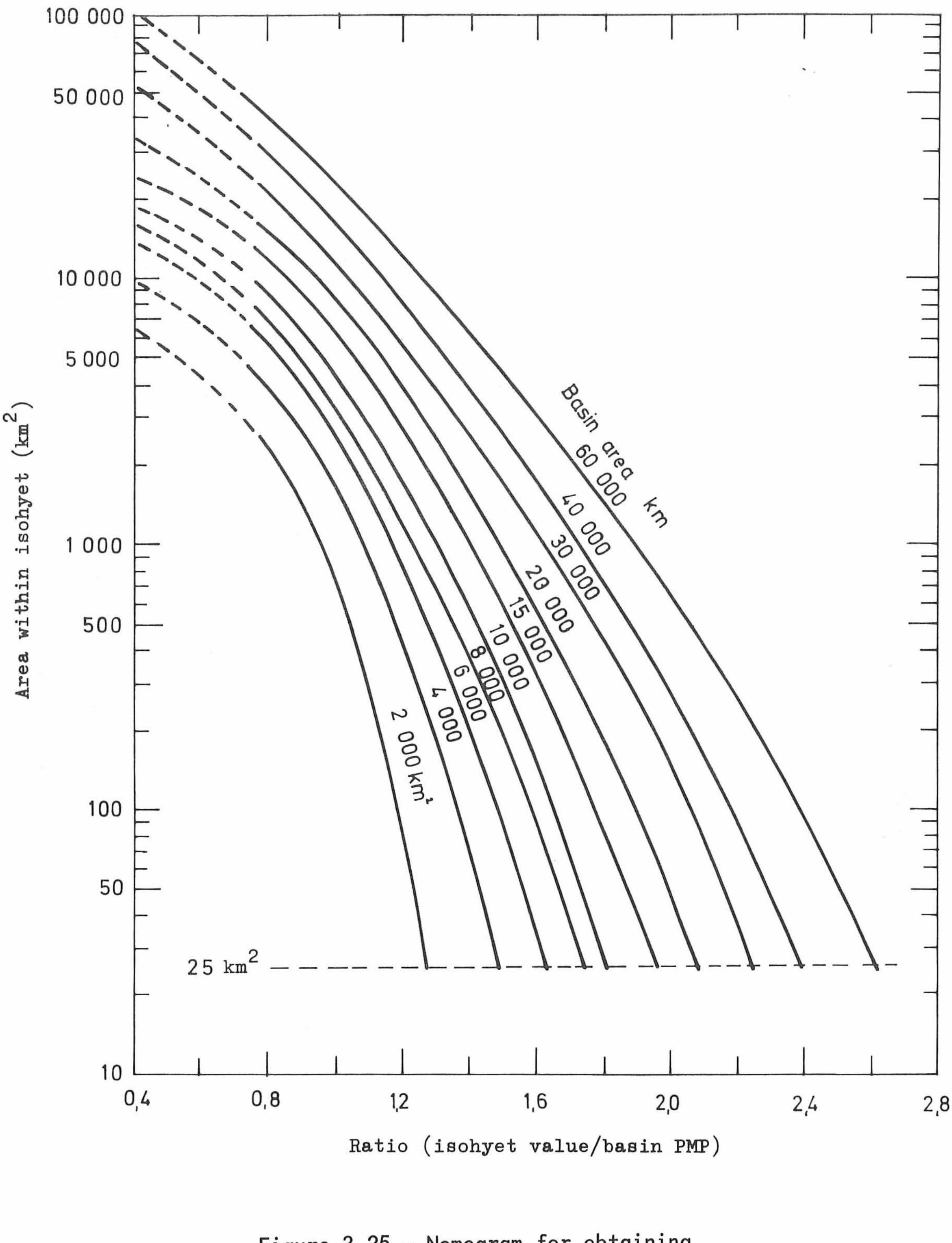

Figure 3.25 - Nomogram for obtaining isohyet values for maximum 6-hour rainfall increment in pattern storms

Table 3.5 - Isohyet values (mm) for 6-hour March PMP storm pattern of Figure 3.24

Isohyet	A	B	C	D	E	F	G	H	P_1	P_2
72 hours	498	470	439	378	371	333	290	241	688	584
1st 6 hours	168	142	135	117	102	86	64	41	241	206
2nd 6 hours	79	76	71	69	64	58	53	41	107	89
3rd 6 hours	53	53	51	46	43	41	40	38	71	61
4th 6 hours	41	41	38	36	33	30	28	25	56	48
2nd day*	99	99	91	61	81	74	69	61	135	114
3rd day**	58	58	53	51	46	43	41	36	79	66
Total area enclosed by isohyet (km^2):	7 120	1 640	18 370	27 530	39 320	55 880	78 000	107 950	2	2

* For successive 6-hour values use 32, 27, 22 and 19 per cent of 2nd day

** For successive 6-hour values use 29, 26, 23 and 22 per cent of 3rd day

The following sequence was recommended on the basis of the above guidelines. It does not necessarily provide PMP for all durations but conforms to observed storm sequences. First, the four largest 6-hour increments of the 72-hour PMP storm were grouped in one 24-hour sequence; the middle four, in a second 24-hour sequence; and the three smallest, in a third 24-hour sequence. Second, the four 6-hour increments within each of these three 24-hour sequences were arranged as follows: second largest next to largest, the third largest adjacent to these, and the fourth largest at either end. Third, the three 24-hour sequences were arranged with the second largest next to largest, with the third at either end. Any possible sequence of the three 24-hour periods was determined acceptable with the exception of that which would place the smallest 24-hour increment in the middle. (Sample arrangement in Table 2.4).

3.5 Cautionary remarks on estimating PMP in orographic regions

The cautionary remarks of section 2.13 concerning adequacy of storm sample, comparison with record rainfalls, consistency of estimates, seasonal variation, and areal distribution apply also to orographic regions. As stated in section 1.3.3, the examples given are not intended for direct application.

3.5.1 Basic data deficiencies

Precipitation networks in orographic regions are relatively sparse compared to those in non-orographic regions, which are generally more heavily populated. Furthermore, in mountainous areas, most gauges are located in settlements at relatively low elevations along rivers or in broad valleys. Very few are located on steep slopes or at high elevations. To these shortcomings may be added the usual deficiencies of gauge measurements, which are likely to be at a maximum in mountainous terrain.

Consequently, precipitation data are not only relatively sparse and sometimes inaccurate but are generally biased and therefore do not represent adequately the effects of orographic influences on precipitation distribution. This shortcoming affects the reliability of various relationships, such as precipitation-elevation and depth-area relations, required for estimating PMP. The situation may be alleviated by referring to adjusted seasonal precipitation maps [2, 6] in determining distribution of storm precipitation (section 3.1.3). Also, it is sometimes possible to use rainfall runoff relations to obtain areal estimates of storm rainfall that may be more accurate then indicated by observed precipitation data alone.

3.5.2 Orographic separation method

The orographic separation method for estimating PMP (section 3.3) involves additional problems besides those just mentioned, since it requires enough upper-air data to obtain reliable extreme values. Model test requirements for upper-air soundings near the inflow side of the test area and for sufficient concurrent precipitation data for the test area further limit the applicability of the model.

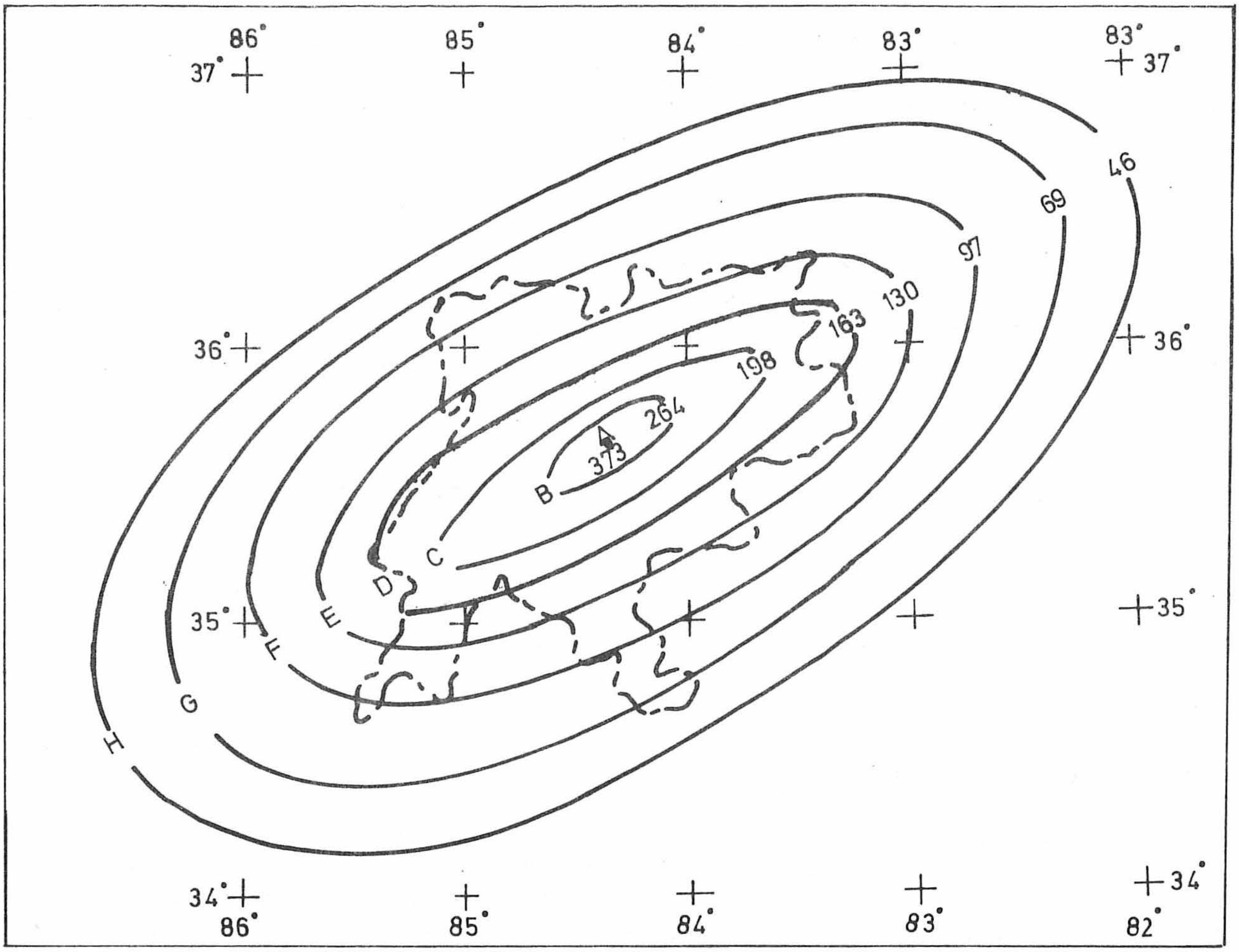

Figure 3.26 - Six-hour March PMP storm pattern (mm) for sub-basin (21 000 km^2)

Of the regions where the orographic model has been tested, best results were obtained for the continuous, high and favourably oriented (with respect to moisture inflow) Sierra Nevada in California. The model computes orographic precipitation under the assumption of laminar air flow. Hence, it is not well suited for regions or seasons where or when unstable atmospheric conditions predominate. Orographic regions where major storms occur in the cool seasons are more likely to meet the required conditions.

Some studies for regions near the tropics indicate that the laminar flow model is unsuited for estimating PMP. Indirect approaches, such as that used for the Tennessee river basin study (section 3.4.2), are likelier to yield more reliable estimates of PMP.

Section 3.3.5 cautioned against over-maximizing and cited some precautions. To these may be added the use of conservative envelopment of the various factors involved in the procedure whenever this technique is required.

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CHAPTER 4

STATISTICAL ESTIMATES

4.1 Use of statistical procedure

Statistical procedures for estimating PMP may be used wherever sufficient precipitation data are available, and are particularly useful for making quick estimates or where other meteorological data, such as dew point and wind records, are lacking. The procedure described below is not the only one, but it has received the widest acceptance. It is used mostly for making quick estimates for watersheds of no more than about 1 000 km^2, but has been used for much larger areas. Its convenience lies in that it requires considerably less time to apply than does the meteorological, or traditional, approach and that one does not have to be a meteorologist to use it. A major shortcoming is that it yields only point values of PMP and thus requires area-reduction curves for adjusting the point values to various sizes of area.

4.2 Development of procedure

4.2.1 Basis

The procedure as developed [3] and later modified [4] by Hershfield is based on the general frequency equation [1]:

$$X_t = \overline{X}_n + KS_n, \tag{4.1}$$

where X_t is the rainfall for return period t; $\overline{X}_n$ and S_n are respectively the mean and standard deviation of a series of n annual maxima; and K is a common statistical variable which varies with the different frequency distributions fitting extreme-value hydrologic data.

If the maximum observed rainfall, X_m, is substituted for X_t, and K_m for K, K_m is then the number of standard deviations to be added to $\overline{X}_n$ to obtain X_m, or

$$X_m = \overline{X}_n + K_m S_n \quad . \tag{4.2}$$

Records of 24-hour rainfall for some 2 600 stations, of which about 90 per cent were in the United States, were used in the initial determination of an enveloping value of K_m. Values of $\overline{X}_n$ and S_n were computed by conventional procedures, but the maximum recorded rainfall at each station was omitted from the computations. The greatest value of K_m computed from the data for all stations was 15. It was first thought that K_m was independent of rainfall magnitude, but it was later found to vary inversely with rainfall: the value of 15 is too high for areas of generally heavy rainfall and too low for arid areas. Values of K_m for other rainfall durations were later determined, and its variation with $\overline{X}_n$ for durations of 5 minutes, 1, 6 and 24 hours is shown in Figure 4.1, which indicates a maximum K_m of 20.

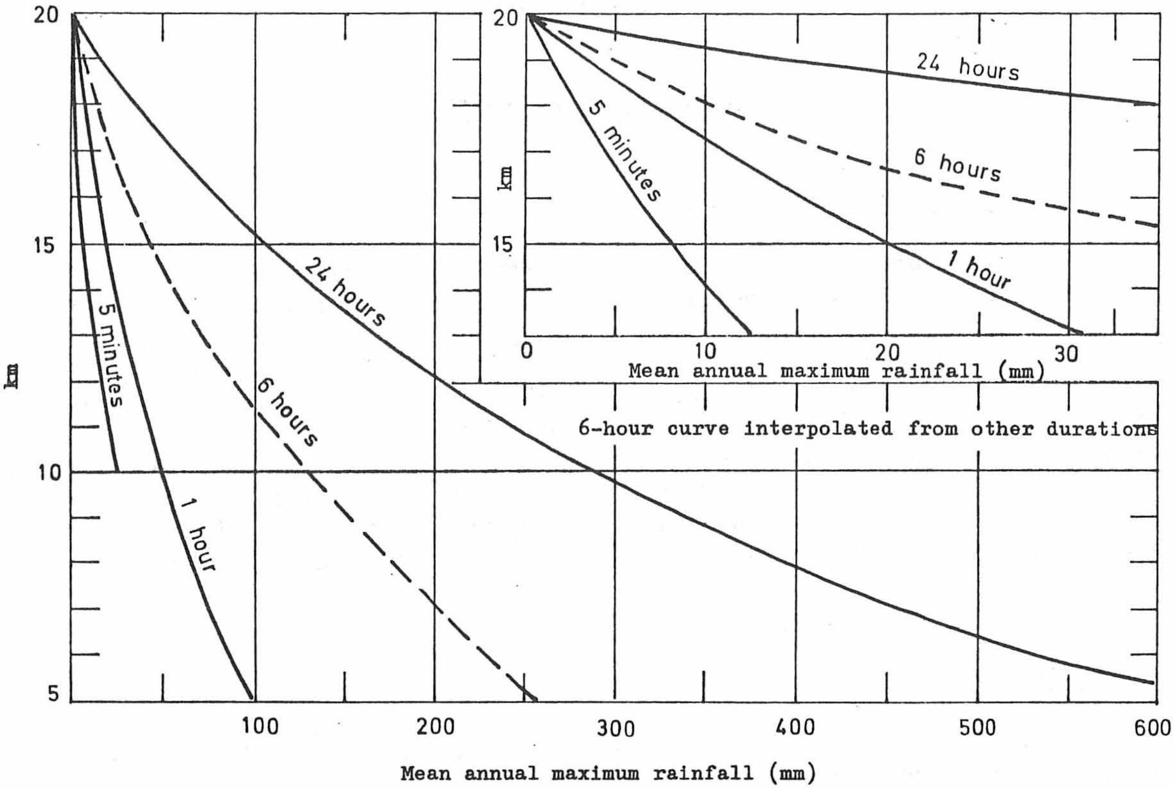

Figure 4.1 - K_m as a function of rainfall duration and mean of annual series (after Hershfield [4])

4.2.2 Adjustment of $\bar{X}_n$ and S_n for maximum observed event

Extreme rainfall amounts of rare magnitude or occurrence, say, with return periods of 500 or more years, are often found to have occurred at some time during a much shorter period of record, say, 30 years. Such a rare event, called an outlier, may have an appreciable effect on the mean ($\bar{X}_n$) and standard deviation (S_n) of the annual series. The magnitude of the effect is less for long records than for short, and it varies with the rarity of the event, or outlier. This has been studied by Hershfield [3] using hypothetical series of varying length, and Figures 4.2 and 4.3 show the adjustments to be made to $\bar{X}_n$ and S_n to compensate for outliers. In these figures $\bar{X}_{n-m}$ and S_{n-m} refer respectively to the mean and standard deviation of the annual series computed after excluding the maximum item in the series. It should be noted that these relationships consider only the effect of the maximum observed event. No consideration was given to other anomalous-appearing observations.

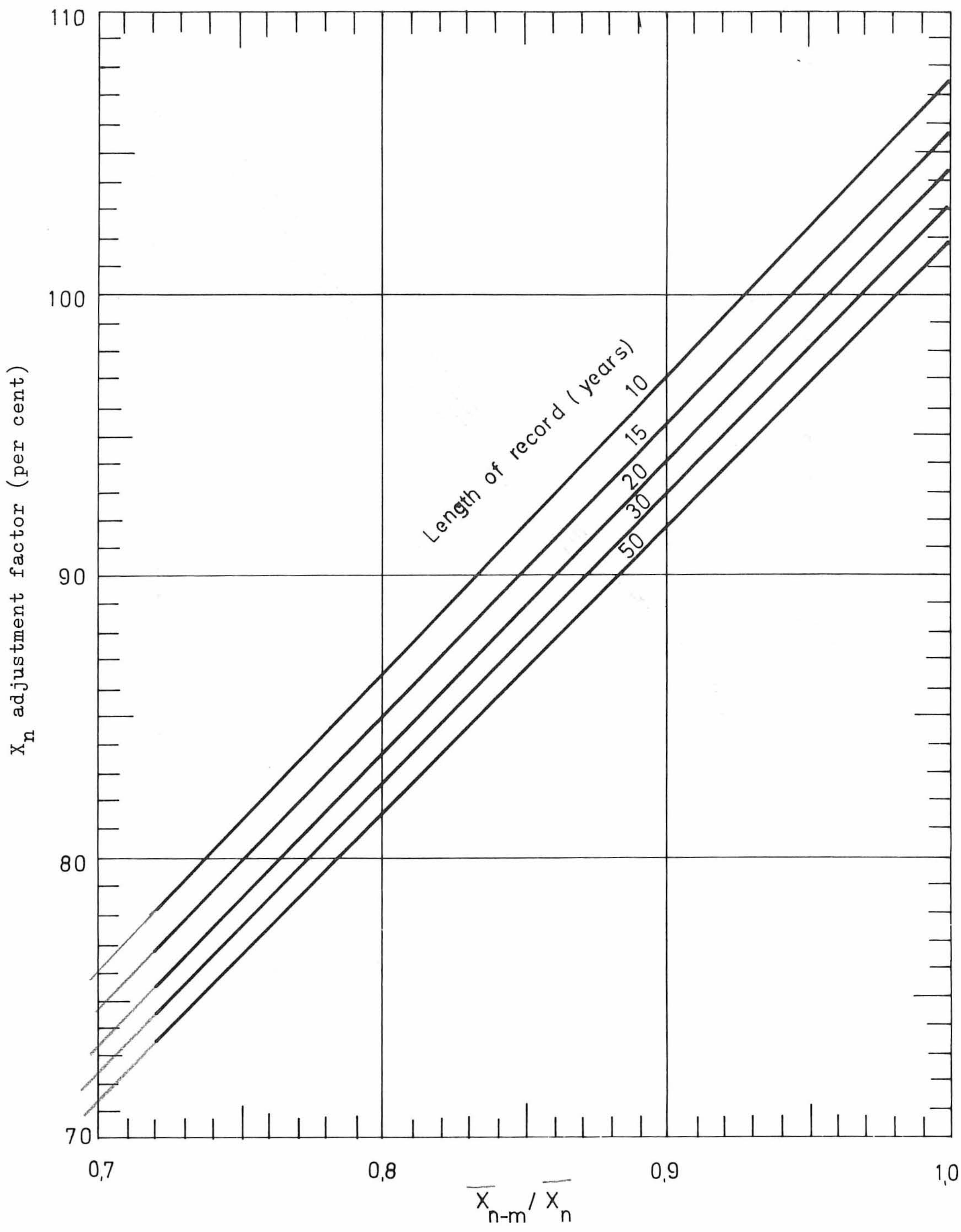

Figure 4.2 - Adjustment of mean of annual series for maximum observed rainfall

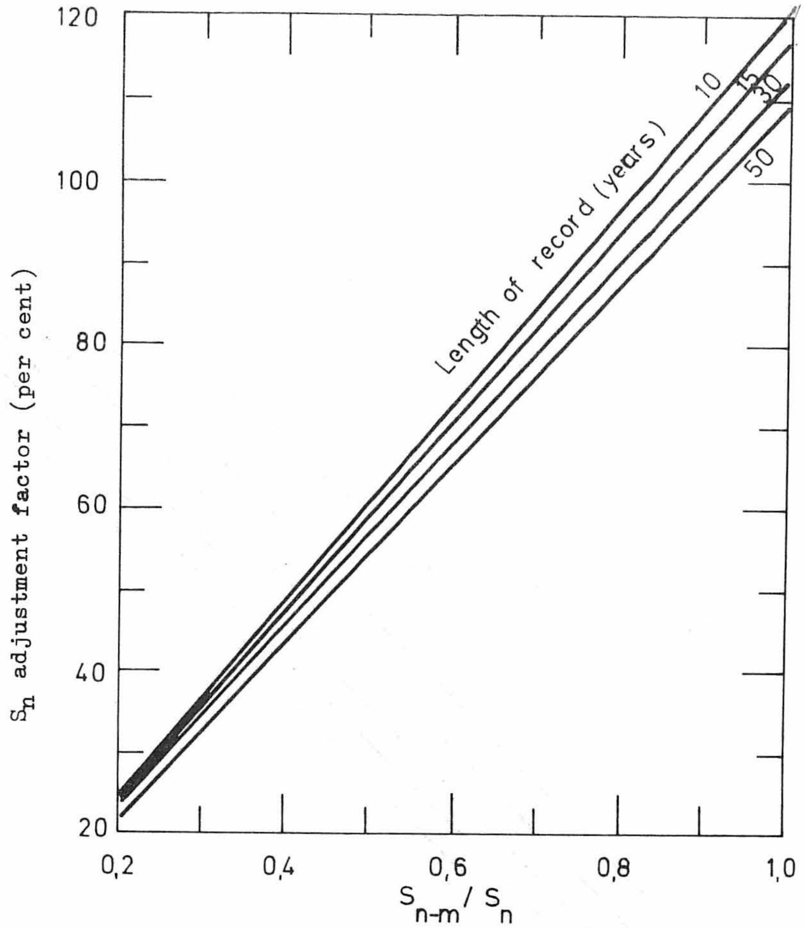

Figure 4.3 - Adjustment of standard deviation of annual series for maximum observed rainfall

4.2.3 Adjustment of $\overline{X}_n$ and S_n for sample size

The mean ($\overline{X}_n$) and standard deviation (S_n) of the annual series tend to increase with length of record, because the frequency distribution of rainfall extremes is skewed to the right so that there is a greater chance of getting a large than a small extreme as length of record increases. Figure 4.4 shows the adjustments to be made to $\overline{X}_n$ and S_n for length of record. There were relatively few precipitation records longer than 50 years available for evaluating the effect of sample size, but the few longer records available indicated adjustment only slightly different from that for the 50-year records.

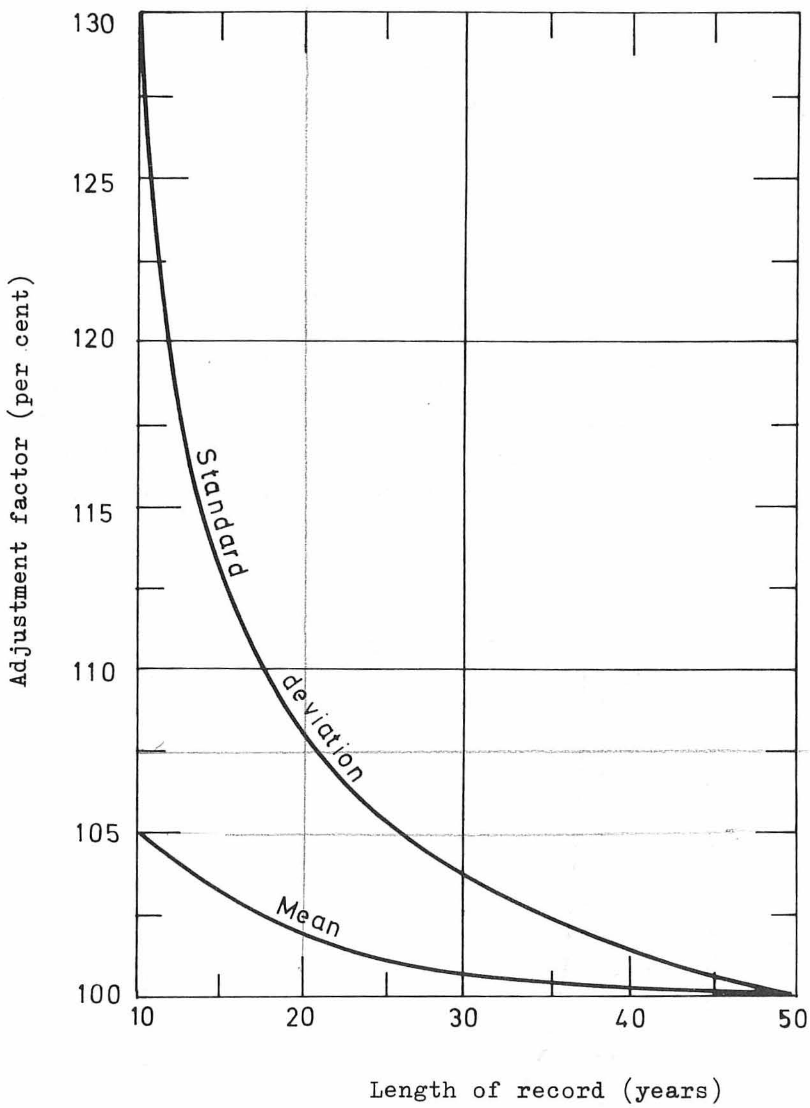

Figure 4.4 - Adjustment of mean and standard deviation of annual series for length of record (after Hershfield [3])

4.2.4 Adjustment for fixed observational time intervals

Precipitation data are usually given for fixed time intervals, e.g., 8 a.m. to 8 a.m. (daily), 0600-1200 (six-hourly), 0300-0400 (hourly). Such data rarely yield the true maximum rainfall amounts for the indicated durations. For example, the annual maximum observational day amount is very likely to be appreciably less than the annual maximum 24-hour amount determined from intervals of 1 440 consecutive minutes unrestricted by any particular observation time. Similarly, maxima from fixed 6-hourly and hourly intervals tend to be less than maxima obtained from 360 and 60 consecutive one-minute intervals, respectively, unrestricted by fixed beginning or ending times.

Studies of thousands of station-years of rainfall data indicate that multiplying the results of a frequency analysis of annual maximum rainfall amounts for a single fixed time interval of any duration from 1 to 24 hours by 1.13 will yield values closely approximating those to be obtained from an analysis based on true maxima. Hence, the PMP values yielded by the statistical procedure should be multiplied by 1.13 if data for single fixed time intervals are used in compiling the annual series. Lesser adjustments are required when maximum observed amounts for various durations are determined from two or more fixed time intervals (Figure 4.5). Thus, for example, maximum 6- and 24-hour amounts determined from 6 and 24 consecutive 1-hour rainfall increments require adjustment by factors of only 1.02 and 1.01, respectively.

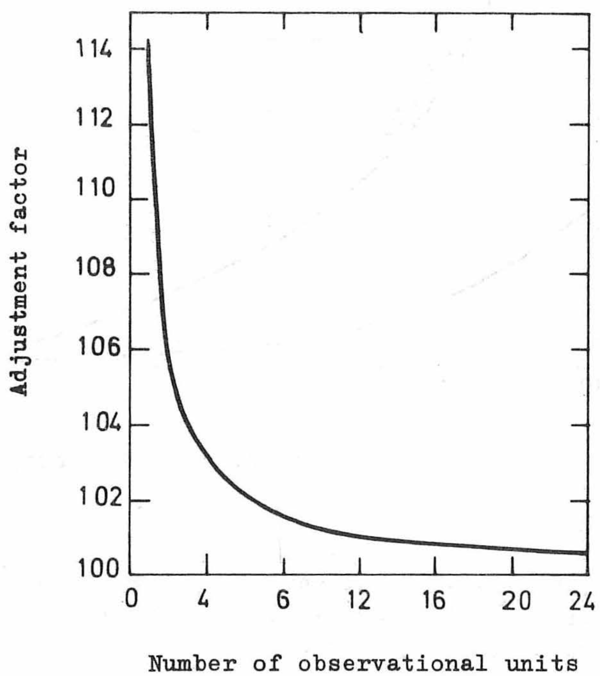

Figure 4.5 - Adjustment of fixed interval precipitation amounts for number of observational units within the interval (after Weiss [8])

4.2.5 Area-reduction curves

The procedure described here was developed for point rainfall data. Hence, its use requires some method for reducing the point values it yields to some required areal rainfall averages. There are many variations of depth-area relationships [27], since they represent the depth-area-duration (DAD) characteristics of different types of storms. The curves of Figure 4.6 [7] are based on average values obtained from DAD analyses of major general-type storms and do not show as much decrease with increasing area as would curves based on localized cloudbursts. They do not extend beyond 1 000 km^2 because extrapolation of point rainfall values becomes more unreliable as size of area increases. Necessity, however, has led to relationships [6] relating point values to areas in excess of 100 000 km^2. Point values are often assumed to be applicable to areas up to 25 km^2 without reduction.

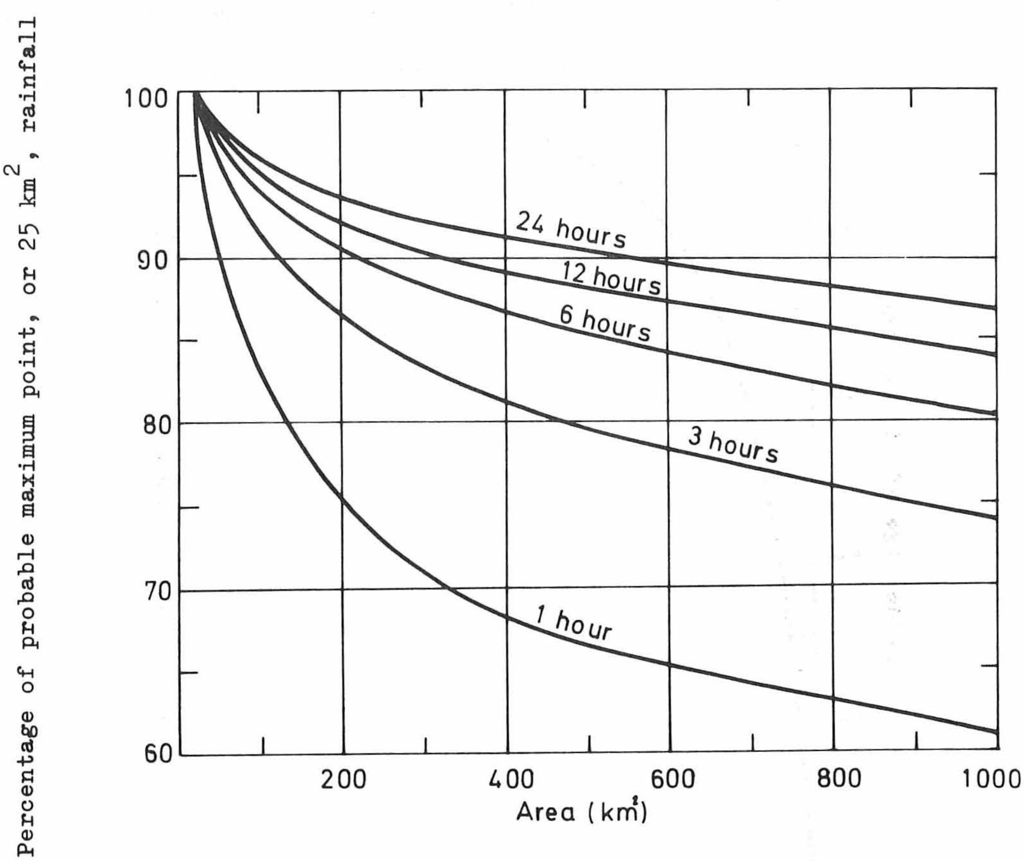

Figure 4.6 - Depth-area, or area-reduction, curves

4.2.6 Depth-duration relationships

Only daily measurements of precipitation are available for many regions. Various types of depth-duration relationships have been developed to show rainfall distribution within storms. Such relationships vary a great deal depending on storm type. For example, orographic rainfall will show a much more gradual accumulation of rainfall with time than will thunderstorm rainfall.

The maximum depth-duration relation of Figure 4.7 is based on rainfall amounts in heavy storms averaged over areas ranging up to 1 000 km^2 in Illinois, U.S.A. [5]. This relationship arranges the rainfall increments for various time intervals in decreasing order of magnitude and not in chronological order. In other words, the curve shows the greatest 3-hour amount in the first 3 hours, the second greatest 3-hour amount in the second 3-hour period, etc. This arrangement is not intended to represent the order in which the rainfall increments occurred, nor does it do so except perhaps accidentally for an occasional storm. Studies of chronological distribution

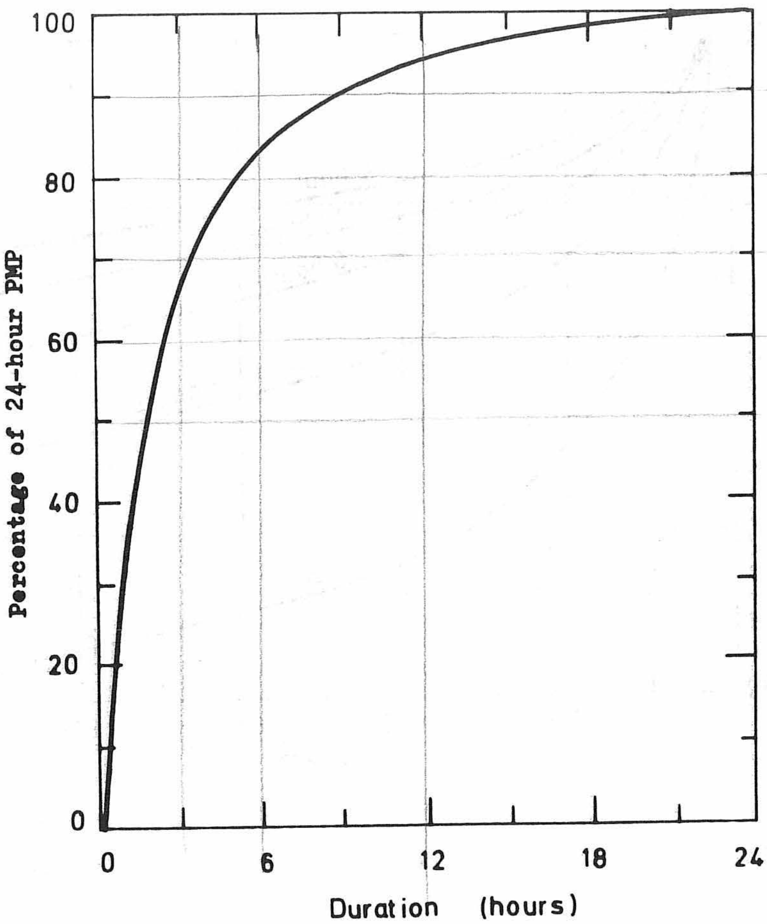

Figure 4.7 - Maximum depth-duration curve

of rainfall within storms indicate no consistent pattern, with maximum intensities likely to occur during any period of the storm.

The curve of Figure 4.7 is representative of convective storms. Because of the variation of such relationships with storm type and geography, they should be developed from data for the same regions for which the PMP estimates are required. Figure 4.7 is presented here merely as an example and is not intended for general application. Figure 4.7, or similar relationships, should be used only when rainfall data for durations shorter than 24 hours are unavailable.

4.3 Application of procedure

It is assumed that a PMP estimate is required for a watershed of 500 km^2. Table 4.1 lists the annual maximum 1-, 6-, and 24-hour rainfall amounts (annual series) compiled from an actual 25-year record of hourly precipitation data for a station in the problem watershed. The hourly values are thus for the clock hour, e.g., 0900-1000, and the 6- and 24-hour amounts consist of the greatest sums of 6 and 24 consecutive clock-hour rainfall increments, respectively. $\bar{X}_{n-m}$ and S_{n-m} are the mean and standard deviation, respectively, of the annual series computed after excluding the maximum rainfall amount in each series. $\bar{X}_n$ and S_n are for the series including all items. Means and standard deviations are computed by conventional methods and should be compared with those of nearby stations for consistency. If inconsistent, another station should be used for estimating PMP.

After the two means and standard deviations for each series and their respective ratios have been obtained as indicated in the table, estimation of PMP proceeds as follows.

1. Adjust $\bar{X}_n$ and S_n for maximum observed rainfall by means of Figures 4.2 and 4.3, respectively, and for record length by means of Figure 4.4.

2. From Figure 4.1 obtain values of K_m corresponding to adjusted values of $\bar{X}_n$ for the various durations.

3. Compute point values of PMP, or X_m, as indicated by equation (4.2).

4. If basic rainfall data are for fixed time intervals, adjust upward by applying the factor 1.13 for fixed observational periods or the factors 1.13, 1.02 and 1.01 to 1-, 6-, and 24-hour amounts, respectively, compiled from hourly data (section 4.2.4).

5. Use Figure 4.6 to reduce point values of PMP to the proper areal value for the size of the basin. (Note: if only 24-hour rainfall amounts are available, a maximum depth-duration curve, like that of Figure 4.7, can be used to estimate PMP for the shorter durations. The 34 and 84 per cent adjustments for the 1- and 6-hour amounts, respectively, would yield values of 155 and 382 mm, which are considerably higher than the 103 and 331 mm based on the actual data. Hence, Figure 4.7 does not very well represent the depth-duration characteristics of PMP indicated by the short-duration data for the problem basin).

Table 4.1 - Computation of probable maximum precipitation (PMP)

Annual maximum precipitation, mm (annual series)

Year	Duration (hours)		
	1	6	24
1941	30	62	62
1942	19	38	60
1943	15	39	57
1944	33	108	112
1945	23	49	67
1946	19	39	72
1947	32	50	62
1948	24	30	61
1949	30	39	57
1950	24	38	69
1951	28	58	72
1952	15	41	61
1953	20	47	62
1954	26	68	82
1955	42	124	306
1956	18	43	47
1957	23	39	43
1958	25	48	78
1959	28	80	113
1960	25	89	134
1961	28	33	51
1962	46	72	72
1963	20	47	62
1964	14	34	53
1965	15	40	55

$n = 25$ $\quad \dfrac{\overline{X}_{n-m}}{\overline{X}_n}$: $\quad \dfrac{24.0}{24.9} = 0.96 \quad \dfrac{51.3}{54.2} = 0.95 \quad \dfrac{69.3}{78.8} = 0.88$

$\dfrac{S_{n-m}}{S_n}$: $\quad \dfrac{6.8}{7.9} = 0.86 \quad \dfrac{19.5}{24.0} = 0.81 \quad \dfrac{21.8}{51.9} = 0.42$

(Continued)

Table 4.1 - Computation of probable maximum precipitation (PMP)

(Continued)

Adjustment of means (X_n) for maximum observed amount and record length:

	1 hour	6 hours	24 hours
From Figure 4.2:	0.99	0.98	0.91
From Figure 4.4:	1.01	1.01	1.01
Adjusted X_n:	24.9	53.6	72.4

Adjustment of standard deviations for maximum observed amount and record length:

	1 hour	6 hours	24 hours
From Figure 4.3:	0.98	0.93	0.49
From Figure 4.4:	1.05	1.05	1.05
Adjusted S_n:	8.1	23.4	26.7
K_m (Figure 4.1):	14	14	16

Unadjusted point values of PMP from equation (4.2):

1 hour: PMP = 24.9 + 14(8.1) = 138 mm
6 hours: PMP = 53.6 + 14(23.4) = 381 mm
24 hours: PMP = 72.4 + 16(26.7) = 500 mm

Adjustment of PMP based on hourly data to true maximum values (see section 4.2.4):

1-hour PMP = 1.13(138) = 156 mm
6-hour PMP = 1.02(381) = 389 mm
24-hour PMP = 1.01(500) = 505 mm

(Note: If annual series data had been compiled from fixed observational time intervals instead of hourly data, the adjustment factor for all durations would have been 1.13.)

Adjustment of point PMP to 500 km^2 (Figure 4.6):

	1 hour	6 hours	24 hours
Adjustment factors:	0.66	0.85	0.90
PMP for 500 km^2 (mm):	103	331	445

4.4 Generalized estimates

Where precipitation networks are considered adequate, generalized PMP estimates of reasonable reliability may be made with relative ease. The adjusted mean ($\overline{X}_n$) and standard deviation (S_n) are determined (section 4.3) for each station, and the coefficient of variation (C_v), i.e., the standard deviation divided by the mean, is then computed. Values of C_v, which is considered a more stable statistic than S_n, and $\overline{X}_n$ are plotted on a map, and two sets of isolines are drawn. Values of PMP for any point on the map may then be obtained by estimating $\overline{X}_n$ and C_v from their respective isolines and using the following relation:

$$X_m = \overline{X}_n (1 + K_m C_v). \qquad (4.3)$$

By computing PMP for a fine grid of points, a map showing PMP values directly may then be constructed. Values of PMP, or X_m, obtained from equation (4.3) are subject to the same adjustments described in section 4.3.

4.5 Cautionary remarks

The curves of Figure 4.1 are based on observed data. Consequently, they imply that PMP has already occurred at those stations providing controlling values of K_m. As a matter of fact, there are at least three measurements of rainfall made in other than official gauges that exceed the PMP values to be obtained from the use of Figure 4.1. The reason given for excluding these measurements in developing the procedure was that the accuracy of the measurements was somewhat questionable and that there were no precipitation records for the locations of occurrence from which to compute $\overline{X}_n$ and S_n. Estimates of these parameters for nearby stations indicated that a K_m value of 25 would have yielded PMP values enveloping any measurements ever made in the United States. Computations of K_m for Canada [6] indicated a maximum value of 30 associated with a mean annual maximum 24-hour rainfall amount of 15 mm.

Further studies are needed to determine more reliable values of K_m. It appears likely, for example, that K_m may be related to other factors besides rainfall duration and mean of the annual series. In using the procedure, it should be kept in mind that the indicated K_m values may be too high for some regions and too low in others. In general, the procedure tends to yield values of PMP lower than those to be obtained from meteorological, or traditional, procedures.

In selecting a station for making a PMP estimate for a particular drainage basin, it is important that its precipitation record is reasonably representative. Comparisons of $\overline{X}_n$ and S_n or C_v with nearby stations are recommended. Odd values in the basic data should be examined and discarded if found spurious, or the record for another station should be used. Length of record should be considered also. A long record will yield generally more reliable PMP estimates than will a short record of comparable quality. Wherever possible, records of no less than 20 years should be used and records of less than 10 years should not be used at all.

The use of general area-reduction and depth-duration curves, like those of Figures 4.6 and 4.7, respectively, introduce additional sources of error in the PMP estimates. Such curves should be developed for the regions for which the estimates are to be made since they vary with rainfall type and geography.

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CHAPTER 5

GENERALIZED ESTIMATES

5.1 Generalized charts

The methods of estimating PMP discussed in Chapters 2 and 3 may be used either for individual basins or for large regions encompassing numerous basins of various sizes. In the latter case, the estimates are referred to as generalized estimates, and are usually displayed as isohyetal maps which depict the regional variation of PMP for some specified duration and basin size. These maps are commonly known as generalized charts of PMP.

The chief advantages of generalized PMP charts are: (1) they are a ready source of PMP estimates for any basin in a region, and (2) they are very useful in maintaining consistency between estimates made for individual basins within a region.

Within any particular region, variations in topography tend to increase as basin size increases, and preparation of generalized estimates becomes more complicated, especially in orographic regions. Because of the difficulties, generalized estimates have been generally limited to areas under 10 000 km^2, but some developmental work has been done on such estimates for areas up to about 50 000 km^2.

5.1.1 Base maps

5.1.1.1 Scale

The choice of a suitable map base for developing and depicting generalized estimates of PMP depends chiefly on the size of the region for which the estimates are to be made, the topography, and on the degree of detail to be shown on the final maps. Base maps with a scale of about 1:2 500 000 may be adequate for many non-orographic, i.e. not extremely mountainous, regions. Regions of rugged orography require a larger scale, usually no less than 1:1 000 000, while a smaller scale, say, 1:5 000 000, might be adequate for flat terrain. Whatever the scale, the base maps should show the topography of the region. The final maps used for displaying the estimates may be reduced considerably, of course, but not so much as to make it difficult for the user to locate a basin for which an estimate is required. For this reason, the final maps should show the scale, a latitude-longitude grid, boundaries of states, provinces, districts and countries.

5.1.1.2 Grid system

Once a proper base map is selected, the next step is to construct a grid on the map. The grid is usually constructed to conform with the latitude-longitude grid of the map. The points formed by the intersections of the grid lines (which actually do not have to be drawn) indicate the locations to which the maximized storms are transposed and the maximum values plotted. Several base maps are sometimes required, the number depending on the PMP values to be displayed. For example, one map may be used for developing and displaying 6-hour PMP over 100 km^2, another, for the 24-hour PMP over 1 000 km^2, etc. Regardless of the number of maps required, the use of the same grid on all maps is advisable as it will minimize the work involved in storm transposition.

The fineness or coarseness of the grid depends on the topography. In very flat regions, a grid of 10 latitude degrees by 10 longitude degrees may be adequate. In mountainous regions, a 1-degree grid may be too coarse. It is not necessary to have a uniform grid over an entire region. If a region includes both flat and mountainous areas, a coarse grid may be used over the flat area and a fine one over the mountainous sections.

5.1.2 Durational and areal consistency

In the preparation of a series of generalized PMP charts for a region, it is important that consistency of estimates be maintained within and between the various charts. It is unrealistic to expect variation in PMP between different durations and sizes of area to be irregular and erratic, and smoothing of computed PMP values is justified. Smoothing is in fact mandatory if consistency is to be achieved. The smoothing techniques used are similar to those described in section 2.8.

5.1.2.1 Depth-duration smoothing

In depth-duration smoothing, maximum adjusted rainfall amounts for various durations and specified size of area for each maximized and transposed storm applicable to a particular grid point or location are plotted on a depth-duration diagram. Figure 2.9 is an example of such a diagram for 2 000 km^2 values at one grid point. The data plotted are the largest maximized rainfall values for each duration, and a smooth curve is drawn to envelop these values.

5.1.2.2 Depth-area smoothing

Smoothing and envelopment across area sizes is similar to depth-duration smoothing. Here, maximum adjusted rainfall values for varius sizes of area and a specified duration for each maximized and transposed storm applicable to a particular grid point or location are usually plotted on semilog paper, with size of area being plotted on the log scale. Figure 2.10 shows such a plotting for 24-hour PMP. The data plotted at 2 000 km^2 are the same data used in Figure 2.9.

5.1.2.3 Combined depth-area-duration smoothing

Depth-area and depth-duration smoothing is sometimes performed in one operation. This is normally done by plotting the data for various durations and sizes of area on one chart like that of Figure 2.11, with each plotted point being labelled with the appropriate storm identification and duration. Smooth isopleths are then drawn.

The combined smoothing procedure is sometimes confusing because of the relatively large amount of data plotted for each duration and size of area. The procedure is simplified by first subjecting the data to separate depth-duration and depth-area smoothing as described in sections 5.1.2.1 and 5.1.2.2. The values plotted on the combination chart are then taken from the enveloping depth-duration and depth-area curves. There is then only one value for each duration and size of area, as shown in Figure 2.11.

5.1.3 Regional smoothing

Isohyets of PMP are drawn to the smoothed storm rainfall values plotted at the grid points on the map. Limits of transposition of storms will usually result in discontinuities between some adjacent grid points. Regional smoothing must therefore take into account the effect of an extreme storm beyond the limits of its area of transposability. In drawing smooth isohyets, meteorological factors, such as moisture source, storm tracks, moisture barriers, etc., need to be considered. Some plotted values may be undercut while others may be over-enveloped. This is done when data appear inconsistent with nearby values, and to draw for them would result in unwarranted bulges or dips in otherwise smooth isohyets. If there are geographic factors, such as an extended range of high hills in a plains region, to support suspected inconsistent data, isohyets should, of course, be drawn to the data. If data at individual grid points have been smoothed properly (sections 5.1.2.1, 5.1.2.2), little over-envelopment or undercutting is required. Envelopment and undercutting are more commonly done in orographic regions.

5.1.3.1 Supplementary aids

Drawing of isohyets between grid points is often facilitated by supplementary considerations. These considerations apply only to isohyetal gradients and patterns, and have little or no effect on magnitude of PMP values plotted at grid points. In other words, they provide guidance in spacing and shaping of isohyets between grid points while giving greatest weight to plotted values.

Guidance is provided by various types of climatological data. For example, a chart of maximum observed 24-hour point rainfall values from long observational records should show some resemblance to a generalized chart of 24-hour PMP for any size of area up to about 1 000 km^2. Rainfall-frequency charts may also be used for guidance, although they are not so reliable an indicator of regional variation of PMP since frequency is involved rather than magnitude alone. Similar regional patterns may be found also between charts of maximum observed point rainfalls for relatively long durations, say three consecutive days, and generalized PMP charts for large areas, say 10 000 to 50 000 km^2.

Regional similarity of generalized PMP and precipitation frequency patterns does not prevail in those regions where one type of storm produces a large number of heavy rainfalls, but a different type provides outstanding amounts. An example of this lack of similarity is found on the island of Hawaii. There, frequent heavy showers associated with north-east trade winds produce high rainfall-frequency values, while extreme rainfalls invariably occur with the breakdown of these trade winds, and generally with winds from a much different direction. This climatic feature is reflected in differences between generalized PMP and rainfall-frequency patterns (Figure 5.1).

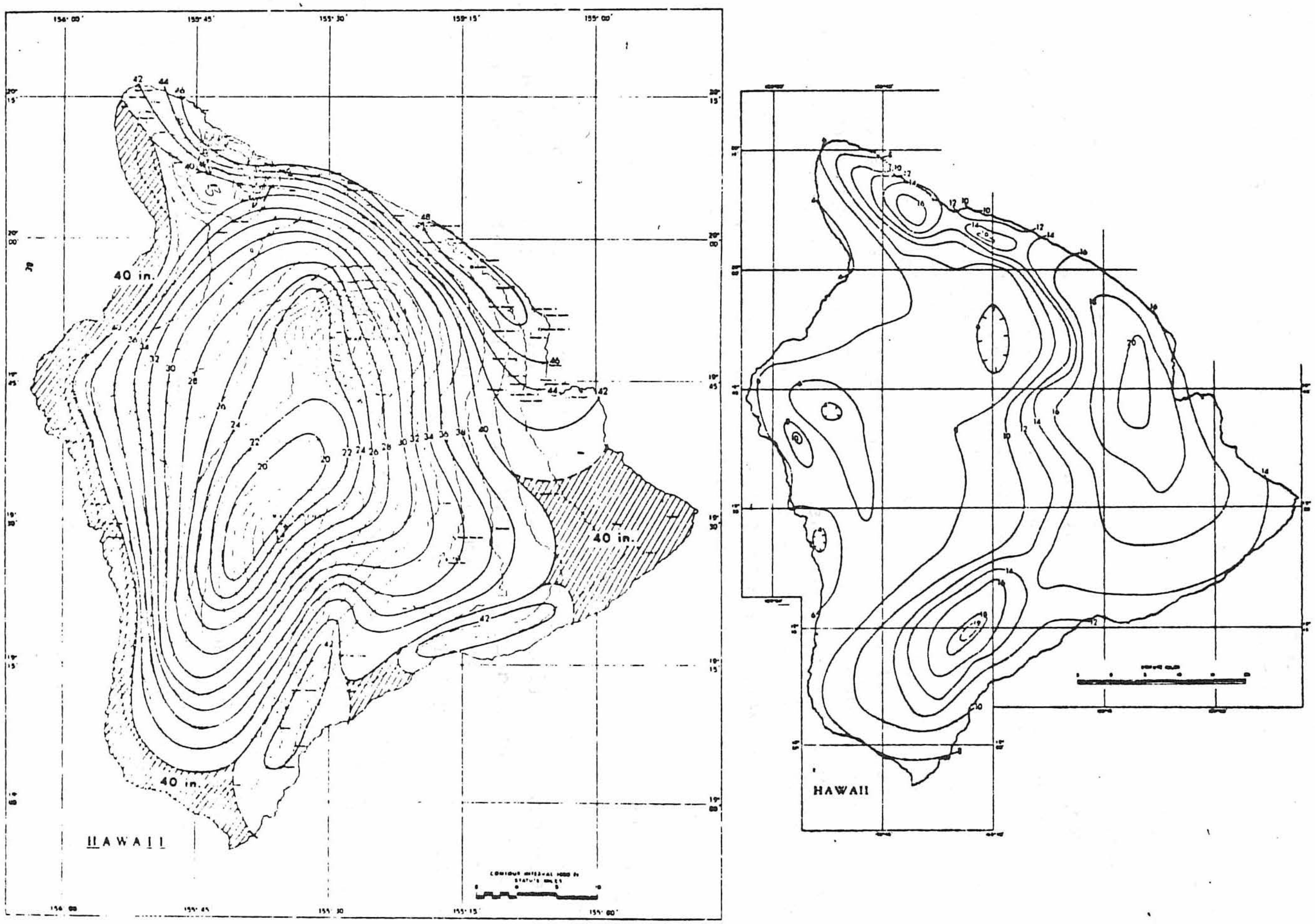


Figure 5.1 - Contrast in PMP and 25-year rainfall patterns, both for 24 hours at a point, Island of Hawaii. Particularly note differences on north-west coast

In orographic regions, relations of intense storm rainfall to elevation, slope, orientation, and other topographic factors may be developed and then used to estimate extreme storm rainfall values. These estimated values provide a distribution pattern that can be used to establish PMP distribution between PMP values at grid points.

5.1.3.2 Maintenance of consistency between maps

In order to maintain consistency between maps when several are to be drawn for various durations and sizes of area, it is recommended that preliminary isohyets be drawn first. Two successive maps in a series are then superimposed on a light table, and final isohyets are then drawn so as to form consistent patterns for both maps. For example, the map of 6-hour PMP for 1 000 km^2 might be superimposed on that for 1-hour PMP for the same size of area. The 6-hour PMP isohyets should, of course, indicate higher values at every point on the map. Also, there is usually no reason for an isohyet on one map to show a dip, or depression, while the isohyet at the corresponding location on another map of about the same duration and size of area in the series shows a bulge. Of course, as differences in duration and size of area increase, there may be gradual changes in patterns so that bulges may eventually become dips or vice versa.

Maps for different sizes of area should be compared and fitted to each other in the same manner. For example, isohyets on a map of 24-hour PMP for 1 000 km^2 should everywhere indicate greater depths than those for 24-hour PMP over 10 000 km^2.

If maps for various months are required, as well as the all-season envelope, seasonal smoothing is necessary. Seasonal variation was discussed in section 2.10.

5.1.4 General remarks

Much work is involved in the preparation of a series of generalized PMP charts for different durations, area sizes, and months. The usual practice is to prepare as few such charts as absolutely required and to provide depth-duration, depth-area, and seasonal variation curves to adjust the chart PMP index values as required. Often, especially for small basin sizes, a single index chart like Figure 3.16 is constructed for a particular duration, area size, and month. Relations similar to those of Figure 3.17 are then developed for making adjustments for other durations, basin sizes and months.

In one study [6], index charts were constructed for 1-, 6-, and 24-hour point PMP, and depth-duration diagrams (Figure 5.2) and area-reduction curves (Figure 4.6) were provided for obtaining PMP values for other durations and area sizes. The depth-duration diagrams (Figure 5.2) were based on maximized rainfall values from major storms. A straight-edge placed on either diagram so that it intersects the first and last verticals at the PMP values indicated on the maps for the corresponding durations will yield the PMP value for any intermediate duration by its intersection with the vertical for that duration. Thus, for example, if 1- and 6-hour PMP values were 250 and 400 mm, respectively, a straight-edge set at those values on the corresponding verticals of the diagram on the left side of Figure 5.2 would show a 2-hour PMP value of 300 mm.

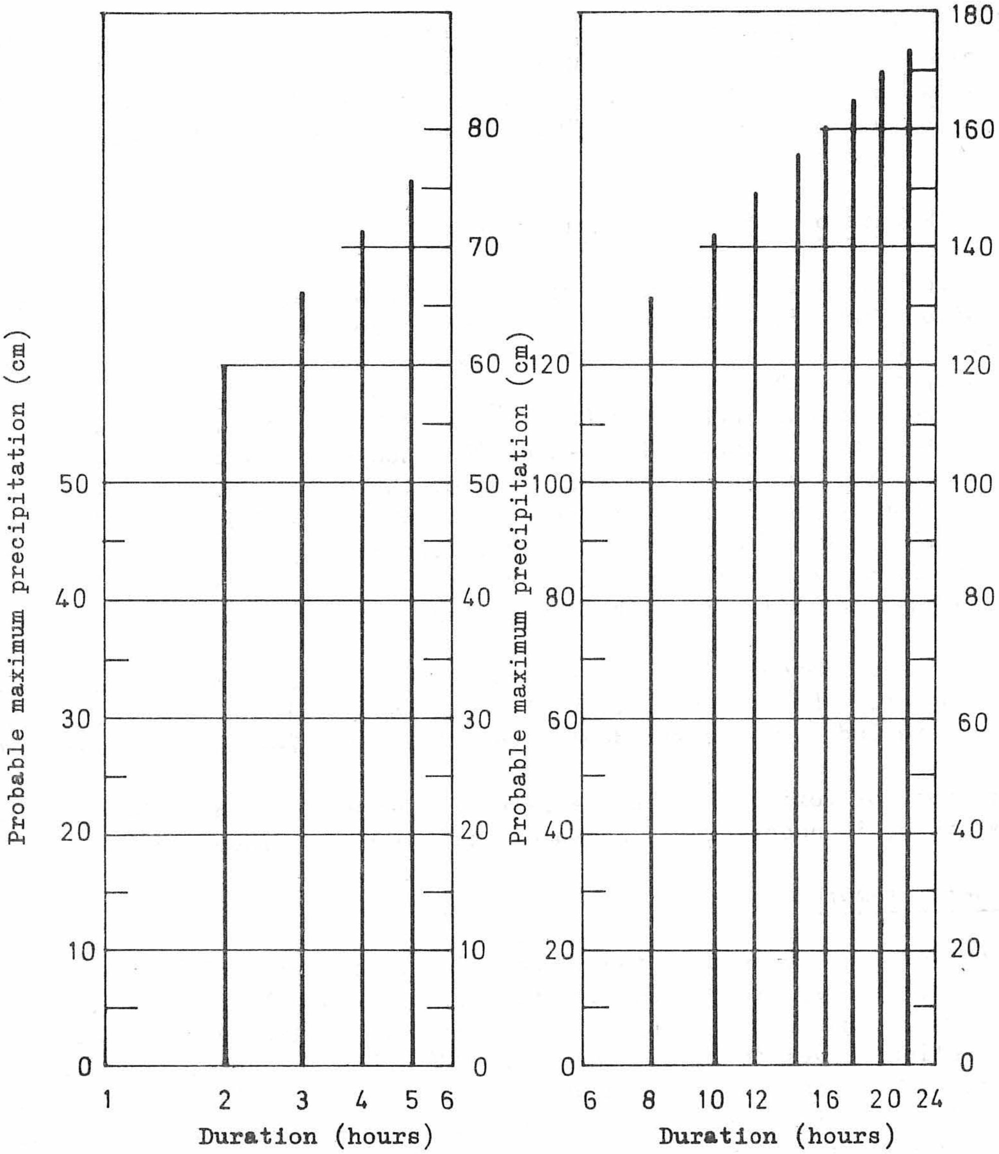


Figure 5.2 - Depth-duration interpolation diagrams

In another study [2], charts of generalized PMP estimates for 24 hours and 500 km^2 were constructed for each month and for the all-season envelope (Figure 5.3). The region covered by these estimates was so large as to involve several different storm régimes. The region was therefore divided into zones, and depth-area-duration relations like that of Figure 5.4 were developed for each zone for every month and the all-season envelope.

Other examples are presented in the discussion of specific generalized PMP studies to be found later in this chapter.

5.2 Estimates for non-orographic regions

5.2.1 Basic procedure

The basic procedure used for making generalized PMP estimates for non-orographic regions is essentially the same as that described in Chapter 2 for individual basins, which involves storm maximization and transposition. Hence, only the procedural modifications required to generalize the estimates are discussed here.

5.2.2 Moisture maximization

The maximum atmospheric moisture available for storm maximization throughout a region is an important requirement for the development of generalized charts of PMP. For reasons given in section 2.2, maximum persisting 12-hour 1 000 mb dew points are used as indices of the maximum amount of atmospheric water vapour available for maximizing storms. Generalized charts of these dew points (Figure 2.4) are therefore required for making the various adjustments involved in developing generalized PMP estimates.

5.2.3 Storm transposition

Storm transposition (section 2.5) plays an important role in the preparation of generalized PMP estimates. In any large region there are many areas that have not experienced or recorded outstanding storms of the magnitude observed in adjacent areas or elsewhere in the region, and transposable storms are adjusted to conditions in these deficient areas to supplement the inadequate record of major storms.

In estimating PMP for a specific basin, major storms are examined to determine if they are transposable to the basin. The storms are then adjusted as required by the geographic features of that particular basin. In the preparation of generalized PMP charts, the boundaries, or limits, of the area of transposability (Figure 2.5) of each major storm are delineated. Each storm is then transposed within its area of transposability to locations indicated by grid points on a suitable base map (sections 5.1.1.2) or to the boundaries of the area, or both. Grid points have the advantage of allowing ready comparisons between rainfall values from different storms.

Transposition of a storm from place of occurrence to another location involves adjustments for differences in geographic features of the two locations (section 2.6). The need for elevation adjustment is minimized if the transposition limits are so delineated that differences in elevation greater than 700 m within the area of transposability are avoided. When this is done, the elevation adjustment discussed in section 2.6.2 is generally omitted.

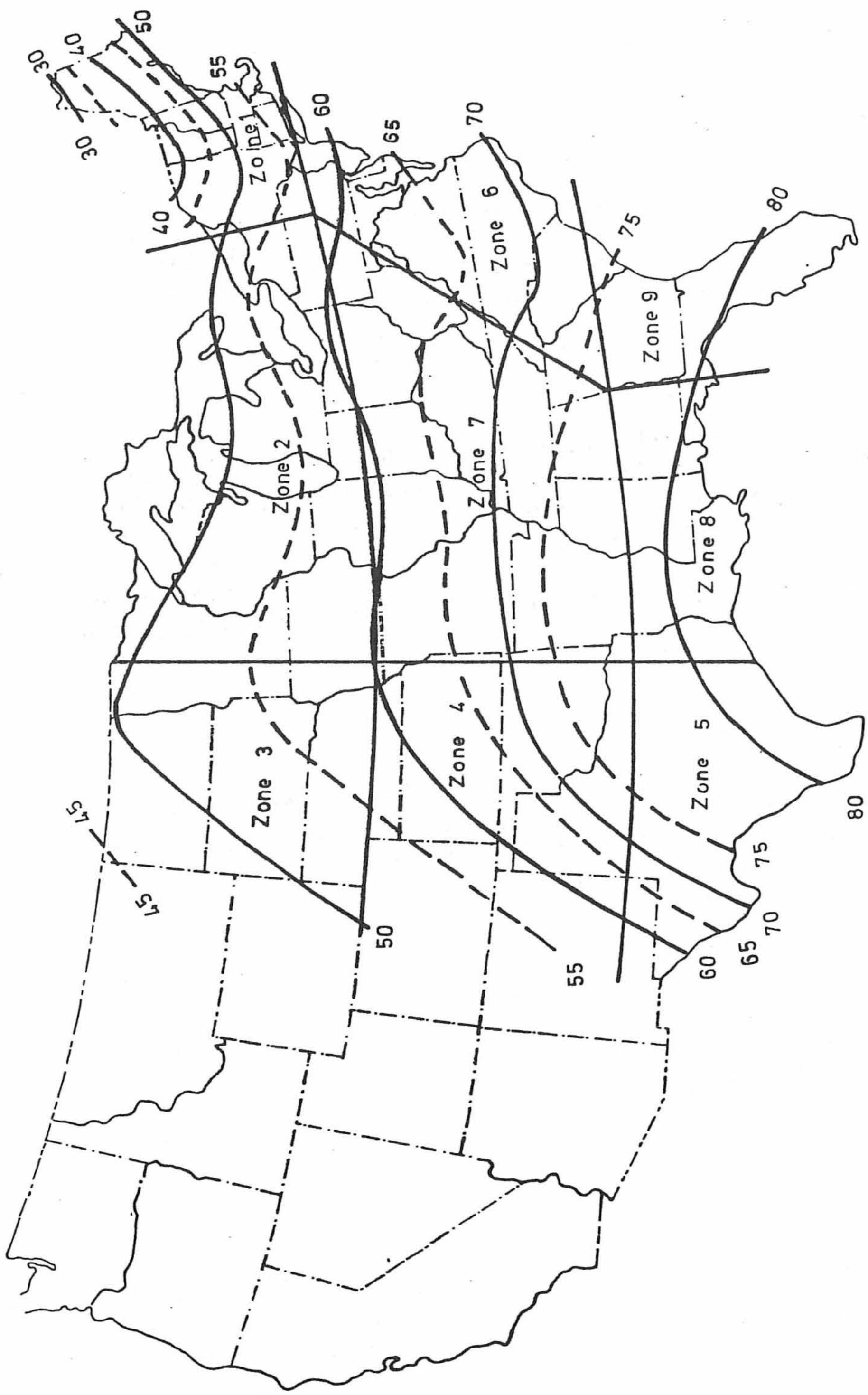


Figure 5.3 - All season envelope of 24-hour 500 km2 probable maximum precipitation (cm)

5.2.4 Summary of procedural steps

The preparation of generalized PMP estimates for non-orographic regions is summarized as follows.

Step 1. Construct an adequate grid system on a suitable base map, or maps (section 5.1.1).

Step 2. Determine areas of transposability of major observed storms in the region of interest and surrounding areas (section 5.2.3).

Step 3. Maximize depth-area-duration values of the selected major storms in place and transposed to grid points in their areas of transposability (sections 2.3 to 2.6). It is rarely necessary to transpose all storms to all grid points since adjustment of a few storms generally indicates which are likely to provide controlling (maximum) values at a particular grid point or set of grid points.

Step 4. Data at each grid point should be checked for durational, areal and seasonal consistency, and smoothed (sections 5.1.2, 5.1.3).

Step 5. Draw preliminary isohyets to the values at each grid point. In drawing the isohyets, data at a few points may be undercut or over-enveloped if the data appear inconsistent with adjacent values and cause unwarranted bulges or dips in the otherwise smooth isohyets. Use whatever supplementary aids are available for spacing and shaping isohyets between grid points and maintain consistency between maps (section 5.1.3). Final isohyets should be smooth, with no unjustifiable dips or bulges.

Step 6. Develop whatever relationships are required to adapt map values to other durations, basin sizes, and months (section 5.1). One generalized chart of PMP for a specific size of area and duration is usually used as an index. PMP for other sizes of area and durations are then obtained from DAD relations, expressed as percentages of the index, developed from all regionally smoothed maps.

5.3 Estimates for orographic regions

5.3.1 Introduction

In orographic regions the problems in deriving generalized PMP charts are much more complex than for non-orographic areas. Differences in topography and its effects, storm types, amount of data available, etc., preclude the development of a standard basic procedure adaptable to the wide variety of situations encountered in making generalized PMP estimates. While such estimates are usually based on non-orographic PMP values modified for orography, the modification procedures differ for different situations. Since there is no standard procedure, summarized examples from actual studies may provide some guidance on how generalized PMP estimates for orographic regions may be made. (See cautionary remarks in section 5.4) The examples presented in the remainder of this chapter were selected to represent a variety of conditions. Generalized PMP estimates made by the orographic separation method were discussed in detail in sections 3.2 and 3.3, and are not included here.

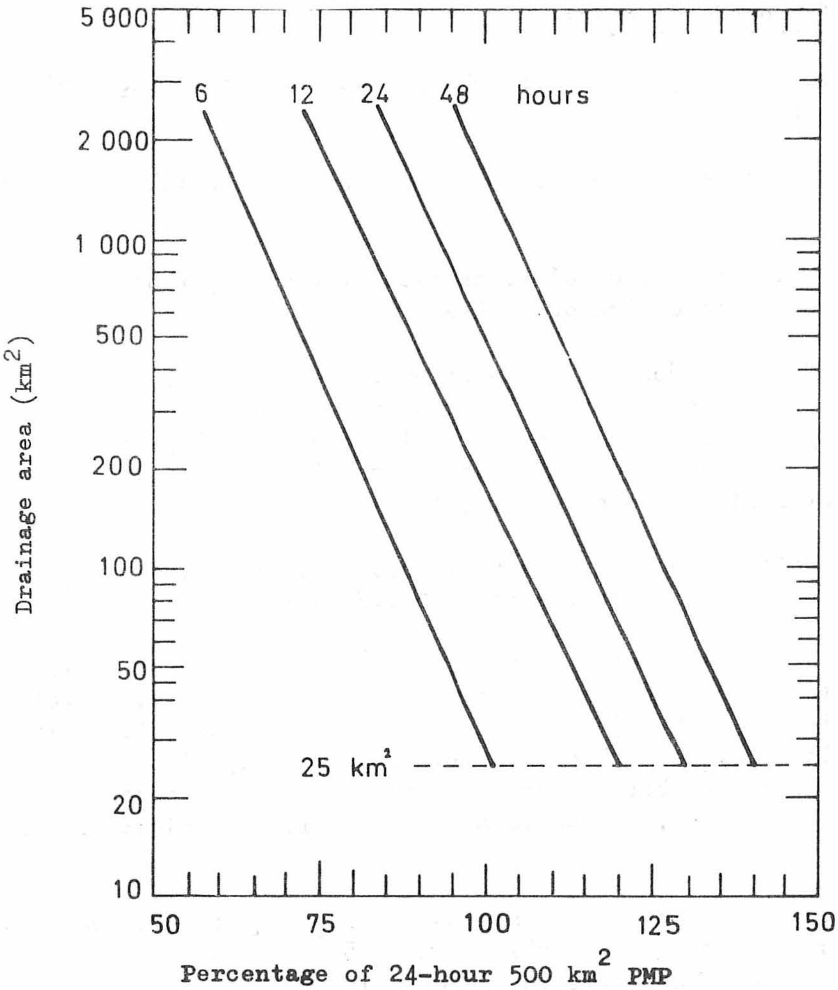


Figure 5.4 - Depth-area-duration relationship for zone 7 of Figure 5.3

5.3.2 Hawaiian Islands PMP

Drainage areas in the Hawaiian Islands are generally less than 120 km^2. Isolated peaks extend above 3 000 m for two of the islands, and to about 1 200 m for three other, larger islands. Numerous investigations have indicated that winds tend to flow around rather than over the higher mountain peaks. Record-breaking rainfall situations feature complex thunderstorms and disturbances of the normally prevailing easterly trade winds. The optimum situation was therefore determined [3] to be a relatively fixed zone of convergence with imbedded regenerative smaller areas of intense vertical motion of the size and intensity associated with thunderstorms. Examination of 156 cases of daily Hawaiian rainfalls exceeding 300 mm disclosed that about 60 per cent were associated with thunderstorms. Thunderstorms were thus revealed as important producers of extreme rainfalls, although, as a general weather feature, severe thunderstorms are relatively uncommon in the Hawaiian Islands.

5.3.2.1 Non-orographic PMP

A basic non-orographic station, or point, 24-hour PMP of 1 000 mm (40 in) was based on the following considerations: (1) the value agreed with world-wide extreme observed non-orographic rainfalls in tropical and subtropical regions, with due consideration for Hawaii's location and limitation on moisture availability; (2) it enveloped maximum observed rainfall amounts in Hawaii by a reasonable margin; and (3) it approximated the value obtained from multiplying the enveloping P/M ratio and appropriate cool-season moisture. Additional support was provided by an earlier estimate of PMP for Puerto Rico [7], which is at about the same latitude as Hawaii.

5.3.2.2 Slope intensification of rainfall

An empirical relation showing rainfall intensification with slope was developed from observed rainfall data in somewhat comparable terrain. These data indicated a decrease in the elevation of maximum rainfall amounts as rainfall intensity increased and an increase of rainfall with ground slope. Precipitation data from various parts of the world were used to determine the general variation in rainfall intensification with ground slope shown in Figure 5.5.

Greatest intensification is shown for intermediate values of slope (about 0.10-0.20). There is almost no intensification for slopes greater than about 0.25. Such steep slopes are generally found at the higher elevations, where winds tend to circumvent the peaks so that there is little large-scale lifting of air over the peaks.

The dashed lines of Figure 5.5 apply to a column of saturated air with a 1 000 mb temperature of 23°C, and show the depletion of moisture with increasing ground elevation. Thus, for any point on the intensification curve, or any given slope, the elevation at which moisture depletion negates rainfall intensification can be determined readily. For example, the critical elevation for a slope of 0.17 is about 1 000 m. Above 1 500 m, moisture depletion outweighs slope intensification for all slopes. This is shown in Figure 5.6, which combines the effects of slope intensification and moisture depletion to provide a slope and elevation adjustment to the basic 24-hour point PMP of 1 000 mm.

5.3.2.3 Generalized PMP estimates

Generalized estimates of 24-hour point (2 km^2) PMP are presented in Figure 5.1. Climatological data showing spillover and other orographic effects were used in modifying the results indicated by the relation of Figure 5.6.

Ratios of PMP to 100-year rainfall were examined and adjustments made to avoid unrealistically high or low ratios. Depth-area-duration relations (Figure 5.7) for extending the basic PMP values to durations from 1/2 to 24 hours and to areas up to 500 km^2 were derived mainly from Hawaiian storms. No seasonal variation curve was required since the greater efficiency and lower moisture of cool season storms balanced the lower efficiency and greater moisture of summer season storms.

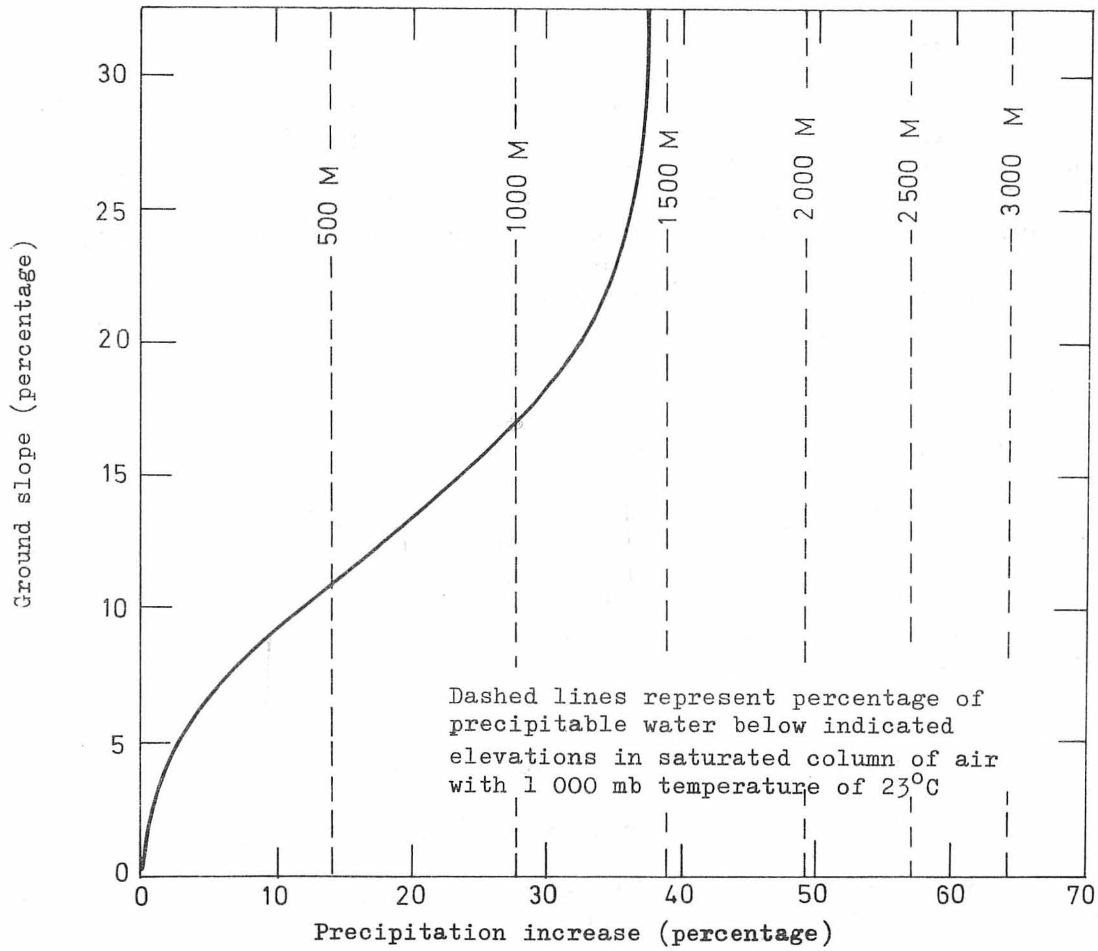


Figure 5.5 - Rain intensification for ground slope, Hawaiian Islands

PMP for a specific basin is obtained by planimetering the area within the basin on the 24-hour point PMP chart (Figure 5.1) to obtain the 24-hour basin-average PMP. The depth-area-duration relation of Figure 5.7 is then used to obtain PMP values for other durations.

5.3.3 PMP for drainages up to 250 km^2 in the Tennessee river basin

The Tennessee river basin above Chattanooga, Tennessee, roughly the eastern half of the entire basin, was described in section 3.4.2. The western half is relatively low, with rolling hills. Generalized PMP estimates have been made [5] for the entire basin for drainages up to about 8 000 km^2. Because of a specific requirement for generalized PMP estimates for small basins up to 250 km^2 and the fact that different types of storms are likely to produce PMP over small and large areas, separate investigations were conducted for these small basins and for drainages between 250 and

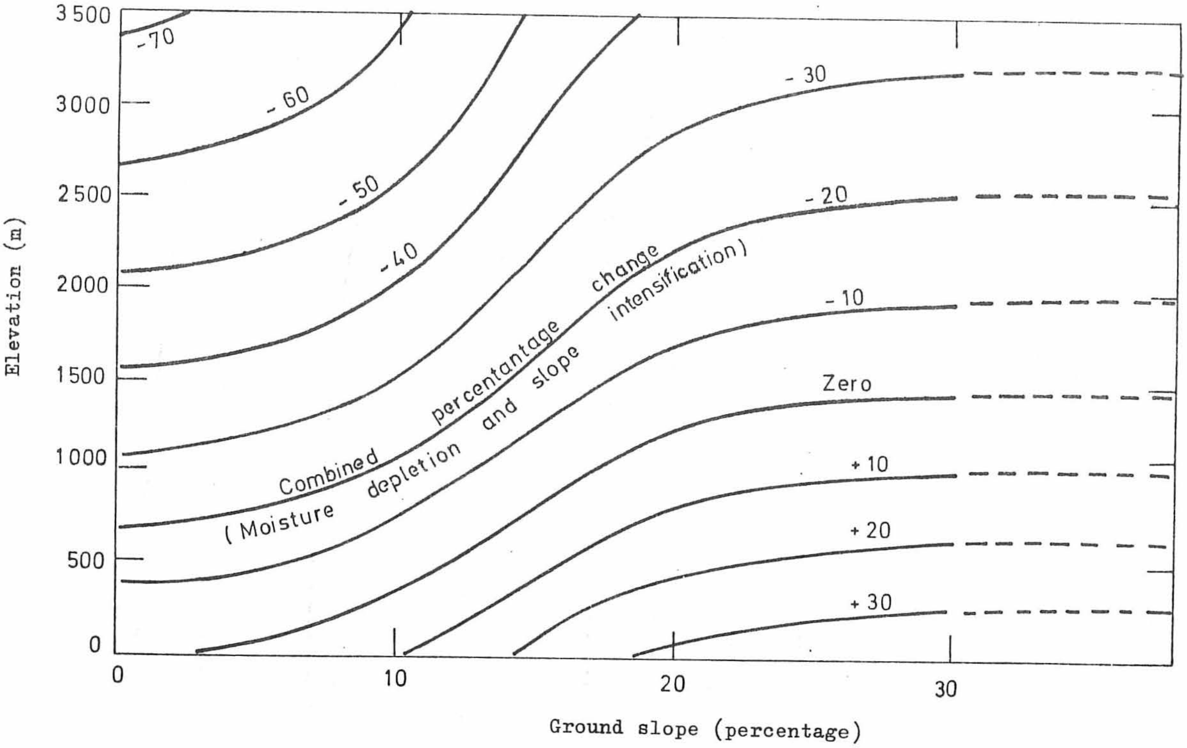


Figure 5.6 - Adjustment of non-orographic PMP for elevation and slope, Hawaiian Islands

8 000 km^2. Only the estimates for the eastern half of the entire basin are described in this manual. The eastern half is referred to hereafter as the project basin. This section deals with estimates for the small basins. Those for the larger basins are discussed in section 5.3.4.

5.3.3.1 Outstanding rainfalls

A record of 56 outstanding point rainfalls in the period 1924-1965, including a few estimates based on run-off computations, in or near the project basin yielded a 1-hour amount and several 3-hour amounts of about 300 mm. Approximate elevations ranging from 200 to over 1 200 m were determined for most of these storms. No unique rainfall-elevation relation was evident. This suggested a procedure for estimating PMP that did not over-emphasize orographic influences on short-duration rainfalls. Neither was there any noticeable definite geographic distribution of these outstanding values.

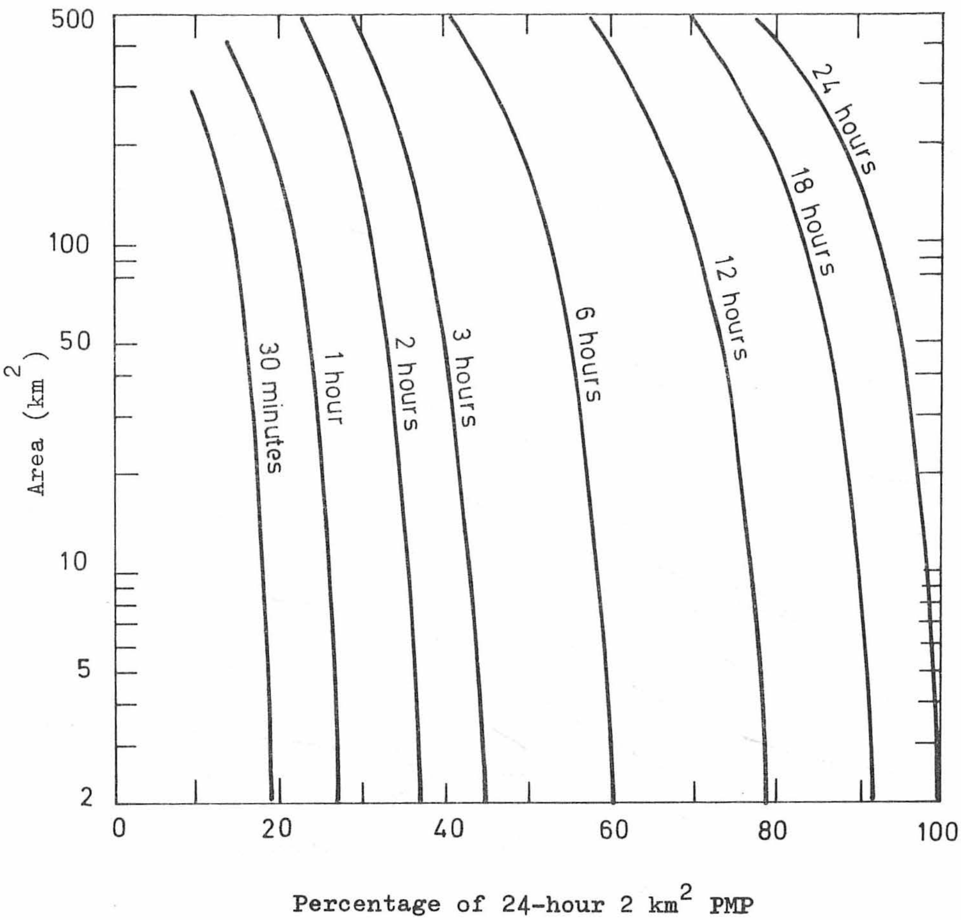


Figure 5.7 - Variation of index PMP with basin size and duration, Hawaiian Islands

In order to supplement the basin data, a survey was made of intense small-area short-duration storms from several hundred storm studies for the eastern half of the country. Attention was given to all storms with 6-hour 25 km^2 rainfall exceeding 250 mm, particularly to those exceeding 350 mm. Some of these storms had durations of 24 hours. A study of 60 of the more severe storms indicated that most of them intensified during night-time hours. This suggested that factors more important than day-time heating were generally responsible for these outstanding storms.

All information gained from the above investigations led to the following conclusions concerning small-area PMP for the project basin: (1) the PMP storm-type situation would involve a continuation of geographically fixed thunderstorms throughout a 24-hour period, and (2) the PMP-type thunderstorm for durations of one hour or less would show little, if any, orographic effect, while that for longer durations would be likely to produce more rainfall on slopes and adjacent valleys than over flat areas with no nearby slopes.

5.3.3.2 Local topographic classification

Examination of manor storm sites by aerial reconnaissance and inspection of large-scale topographic maps (1:24 000) led to the following topographic classifications.

Smooth: few elevation differences of 15 m in 0.5 km.

Intermediate: elevation differences of 15 to 50 m in 0.5 km.

Rough: elevation differences exceeding 50 m in 0.5 km.

Although the entire south-eastern portion of the project basin was classified as rough, there were variations in rainfall potential across the area. Some peaks reached up to almost 2 000 m and some ranges sheltered large valleys. The contrast between high mountains and large sheltered valleys required additional consideration besides roughness in order to assess topographic effects on intense summer rainfalls. The effect of local topography on rainfall is discussed in section 5.3.3.4.

5.3.3.3 Broad-scale topographic effects

Broad-scale topographic effects on rainfall were determined by analysis of maps of maximum observed and 100-year daily rainfalls. Mean annual and seasonal precipitation maps were also examined. After some experimentation, the following concepts evolved and were adopted.

First upslope: a mountain slope facing the lowlands in a direction east to south-west (moisture-inflow directions) with no intervening mountains between the slope and the moisture sources, viz., the Gulf of Mexico and Atlantic Ocean.

Secondary upslope: a secondary upslope high and steep enough to increase precipitation but partially shielded from moisture sources by a lower mountain range with an elevation between crests of at least 500 m.

Sheltered areas: these are defined as valleys having moisture-inflow barriers of 600 m or higher.

Depression: the elevation difference between the barrier crest and a point in a sheltered area is the depression of that point.

Terrain classifications in the project basin are delineated in Figure 5.8. Analysis of summer rainfall amounts for the various classifications led to adoption of the following guides on topographic effects on PMP: (1) precipitation increase of 10 per cent per 300 m from sea-level to 800 m on first upslopes, with no further increase above 800 m; (2) increase of 5 per cent per 300 m from sea-level to all elevations on secondary slopes; and (3) decrease of 5 per cent per 300 m of depression in sheltered areas.

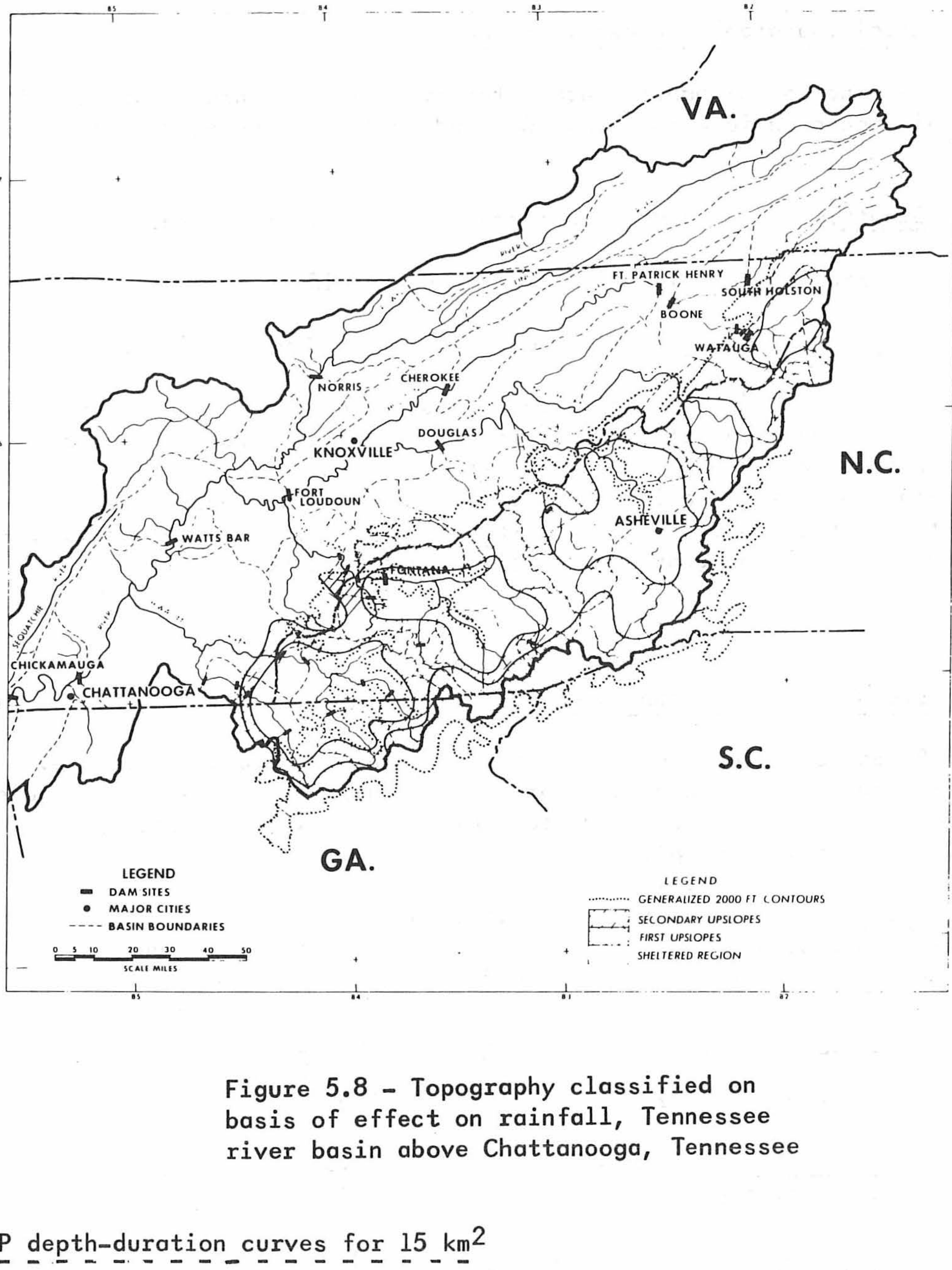


Figure 5.8 - Topography classified on basis of effect on rainfall, Tennessee river basin above Chattanooga, Tennessee

5.3.3.4 PMP depth-duration curves for 15 km^2

Point rainfall values measured in precipitation gauges and similar containers are likely to be less than the maximum point rainfalls experienced but not measured. The maximum point values used were arbitrarily considered to apply to average depths over 15 km^2, the smallest basin size assigned for study. Maximum observed point, or 15 km^2, rainfalls for durations of up to 12 hours in the eastern half of the country were transposed and maximized as described in Chapter 2. Outstanding maximized and observed values were plotted against duration (Figure 5.9), and curves were drawn for smooth and rough terrain (section 5.3.3.2).

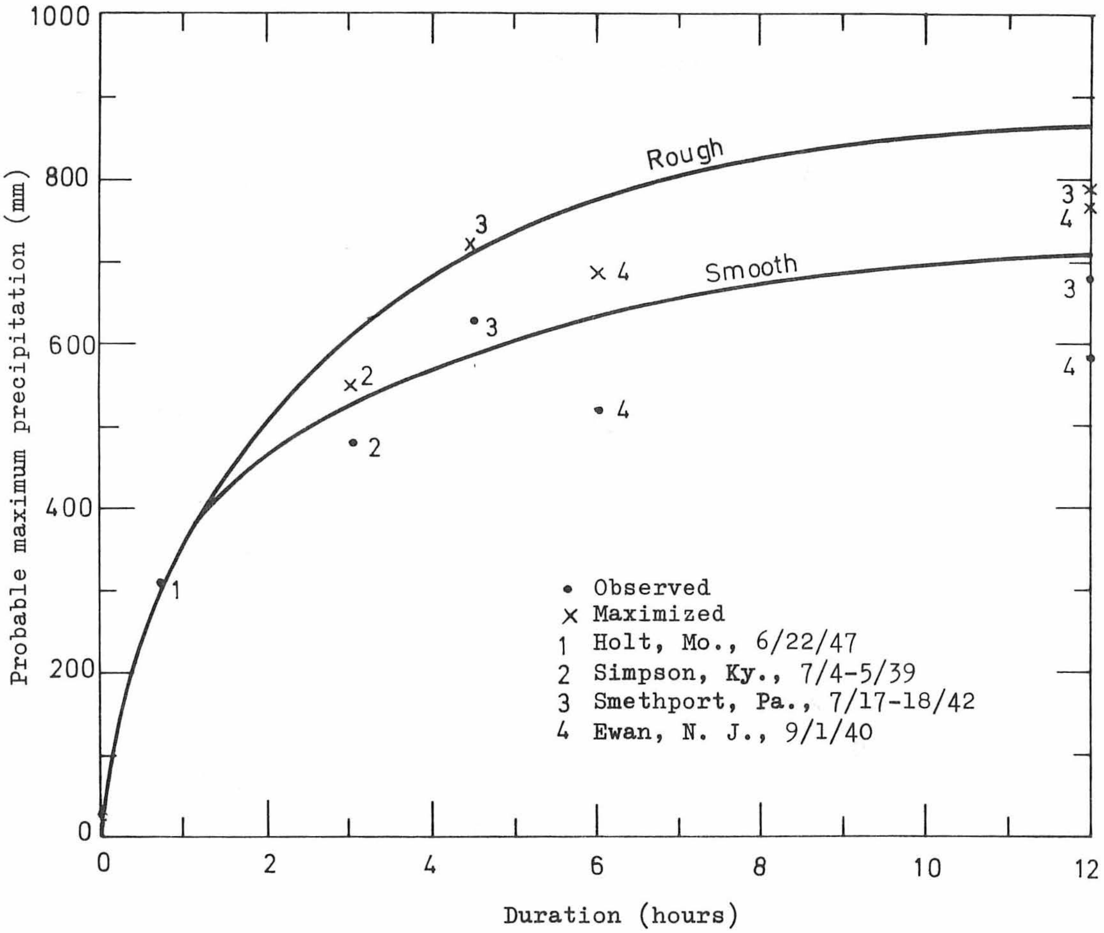


Figure 5.9 - Adopted 15 km^2 PMP with supporting data, Tennessee river basin. (Smooth curve applies to 100 per cent line of Figure 5.12)

The following concepts and principles were observed in constructing the two depth-duration curves. Over areas of a few square kilometres and durations up to about one hour, maximum rainfall rates depend on extreme upward velocities associated with vigorous thunderstorms. These high velocities are related to storm dynamics, and topographic effects are negligible. Hence, the same maximum intensities may be expected within the same air mass over various types of terrain. For longer durations, terrain roughness becomes increasingly important. First, slopes and roughness accentuate upward velocities. Secondly, intense thunderstorms tend to remain at one location longer over a topographically favourable site than over smooth terrain, where they drift with the wind or propogate laterally by their own dynamics. Finally, the probability of continued rainfall after an intense thunderstorm is enhanced by terrain roughness.

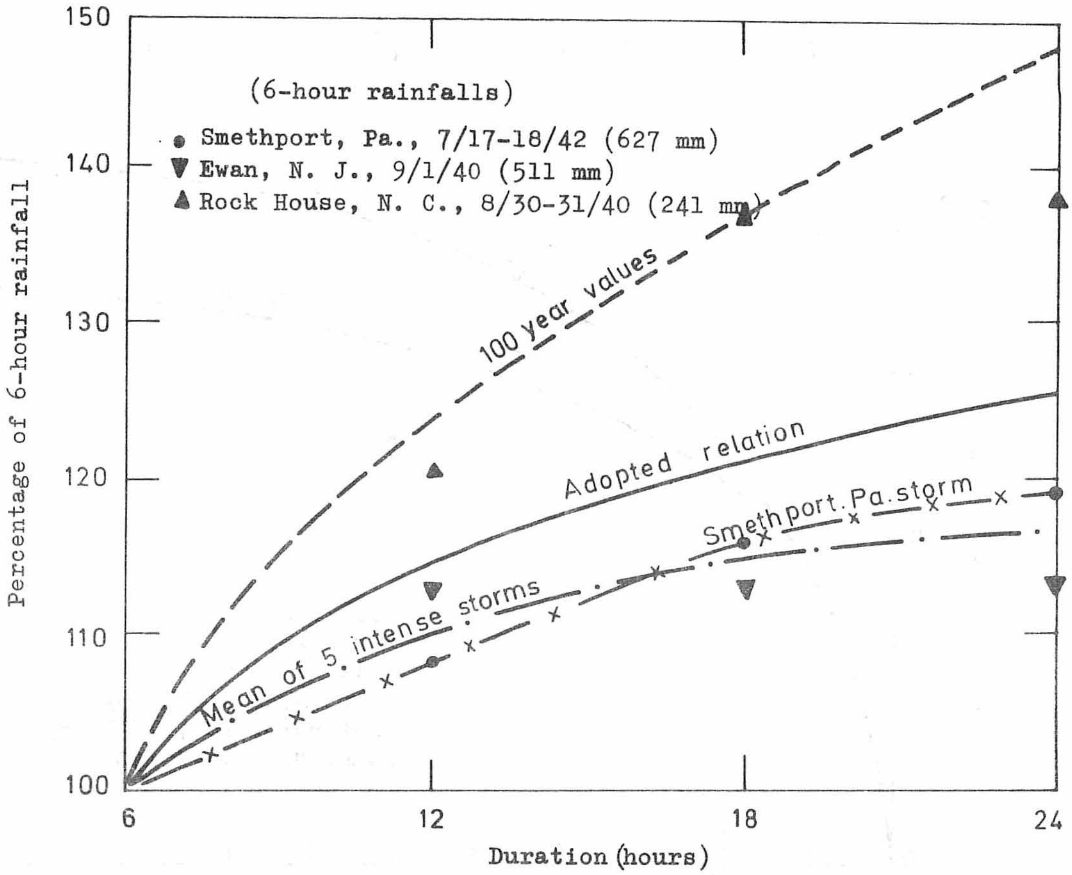


Figure 5.10 - PMP depth-duration curve for basins up to 250 km^2 in Tennessee river basin

Basic 6-hour 15 km^2 PMP values of Figure 5.9 are applicable to the southern edge of the project basin. Smooth PMP in rough terrain is hypothetical but serves as a means for consistent application of adjustments for orographic effects (sections 5.3.3.3 and 5.3.3.5).

Experience with severe storms throughout the country was useful in shaping the depth-duration curves. The curve of Figure 5.10 was developed to extend the curves of Figure 5.9 to durations from 6 to 24 hours.

5.3.3.5 Adjustment for moisture and latitudinal gradient

A moisture adjustment chart was developed for the relatively smooth north-western section of the project basin. This chart (Figure 5.11) was based on an assessment of mean dew points and maximum persisting 12-hour dew points. Analysis indicated a gradient of about 1°C from the extreme south-western corner of the total basin

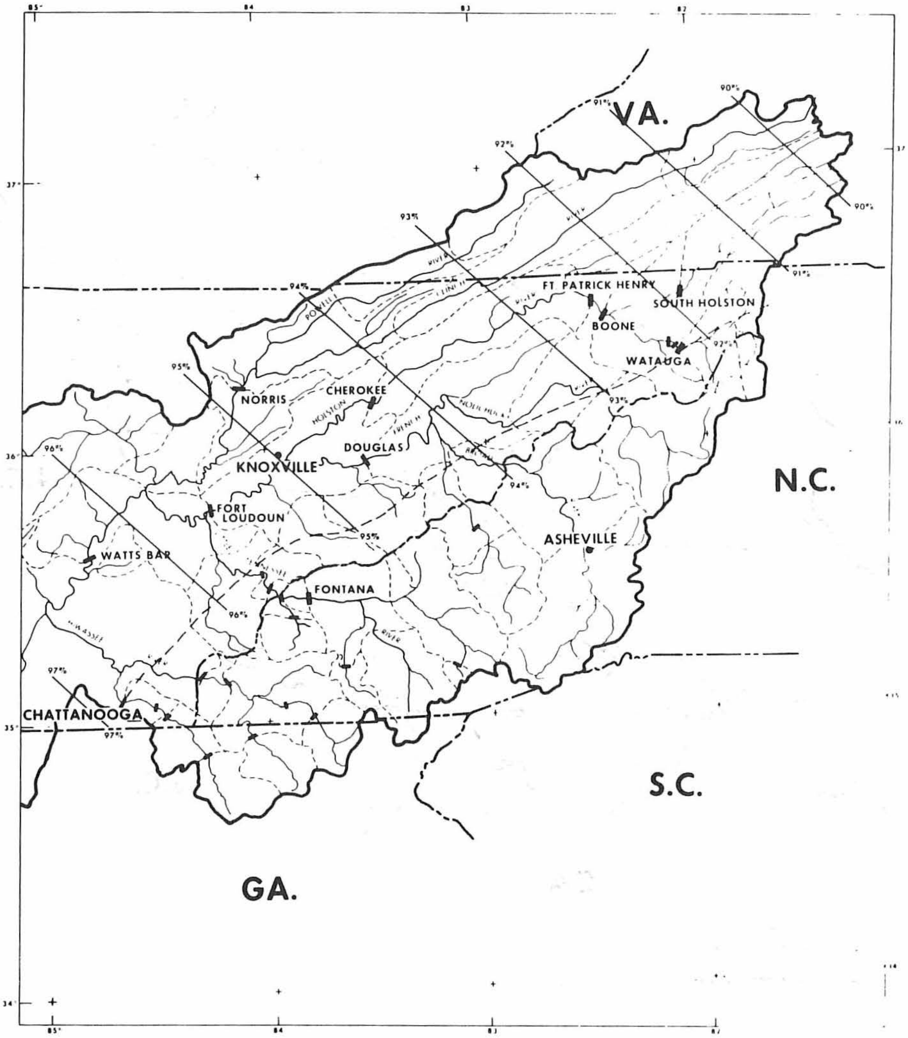


Figure 5.11 - Moisture index chart for north-west portion of Tennessee river basin above Chattanooga, Tennessee

(outside of area shown) to the north-eastern corner, which corresponds to a difference in rainfall of about 10 per cent, according to the usual model for convective rain in extreme storms [1, 6]. Figure 5.11 shows the moisture index lines, in percentages, for adjusting PMP values.

A latitudinal gradient chart (Figures 5.12) was developed for the mountainous portion of the project basin. This chart was based on rainfall-frequency gradients resulting primarily from sheltering by mountains. Moisture effects were incorporated.

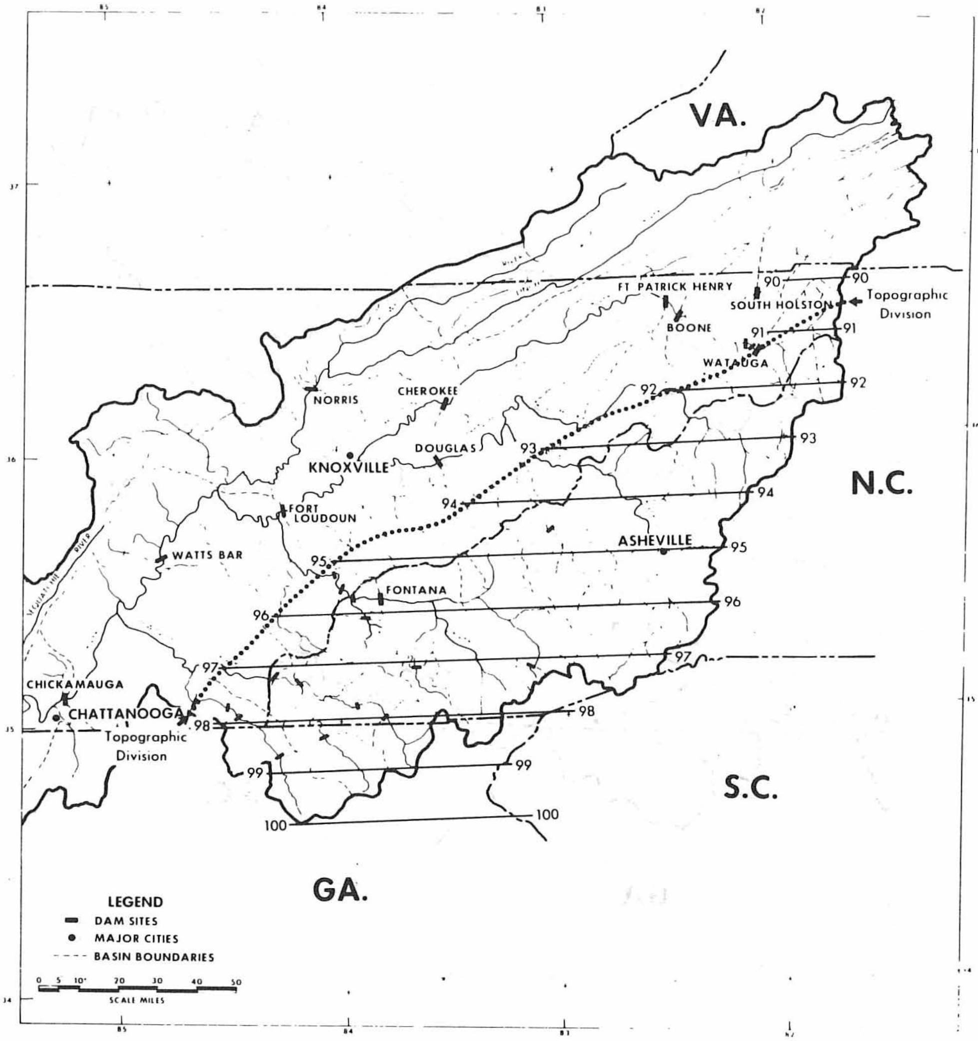


Figure 5.12 - Latitudinal rainfall gradient (in percentage) in south-eastern portion of Tennessee river basin above Chattanooga, Tennessee

5.3.3.6 Six-hour 15 km^2 PMP index map

The concepts and charts discussed above were used to develop the 6-hour 15 km^2 PMP index map (Figure 5.13) for the project basin. Six-hour PMP values from Figure 5.9 of 650, 700 (interpolated) and 750 mm were assigned respectively to smooth, intermediate and rough terrain categories, and multiplied by adjustment factors indicated in Figures 5.11 and 5.12. Isohyets were drawn with steepest gradients corresponding to greatest changes in elevation. This naturally placed steepest gradients where

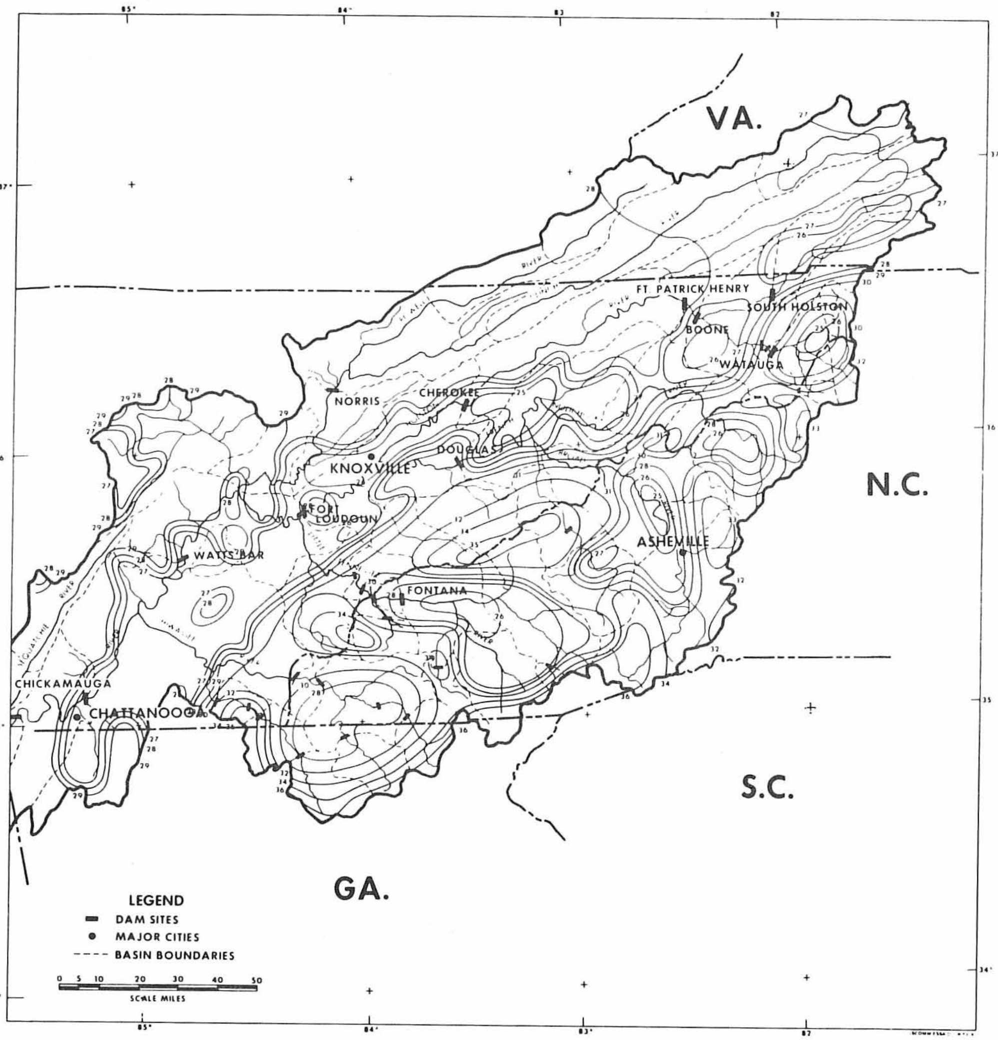


Figure 5.13 - Six-hour 15 km^2 PMP (in) Tennessee river basin above Chattanooga, Tennessee

mountains rise from valley floors. Different adjustments for south-eastern and north-western portions of the basin (Figures 5.11 and 5.12) resulted in some discontinuity at their common boundary, which was smoothed out in drawing isohyets. The final 6-hour 15 km^2 PMP index map is shown in Figure 5.13. A depth-duration relation (Figure 5.14) was developed from a number of PMP depth-duration curves such as Figures 5.9 and 5.10 so that 6-hour PMP could be adjusted to other durations. A depth-area relation (Figure 5.15) was constructed from intense small-area storm data for adjusting the 15 km^2 PMP values to other sizes of area.

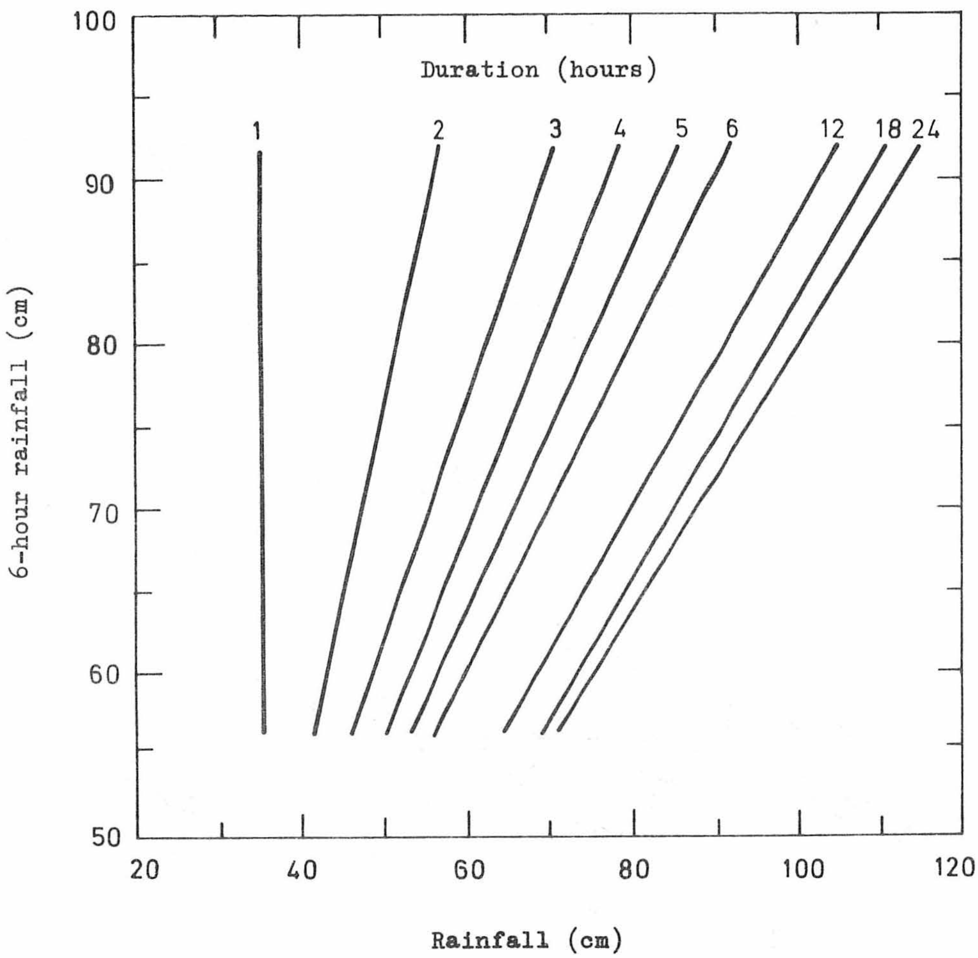


Figure 5.14 - Depth-duration relation for 24 hour PMP storm

5.3.3.7 Time distribution of rainfall

Extreme small-area storms in the project basin generally have been one-burst events in which little rain followed the extreme 3-hour rainfall. Storm experience pointed to the occurrence of a 24-hour rainfall in bursts. The following guidelines were therefore suggested for critical sequences. (1) For 6-hour rainfall increments in a 24-hour storm, the four increments should be arranged with second highest next to highest, third highest adjacent to these two, and fourth at either end. This still allows various arrangements, and the most critical is that which would yield most critical streamflow. (2) For 1-hour increments in the maximum 6-hour increment, any arrangement was acceptable so long as it kept the two highest 1-hour amounts adjoined, the three highest 1-hour amounts adjoined, etc.

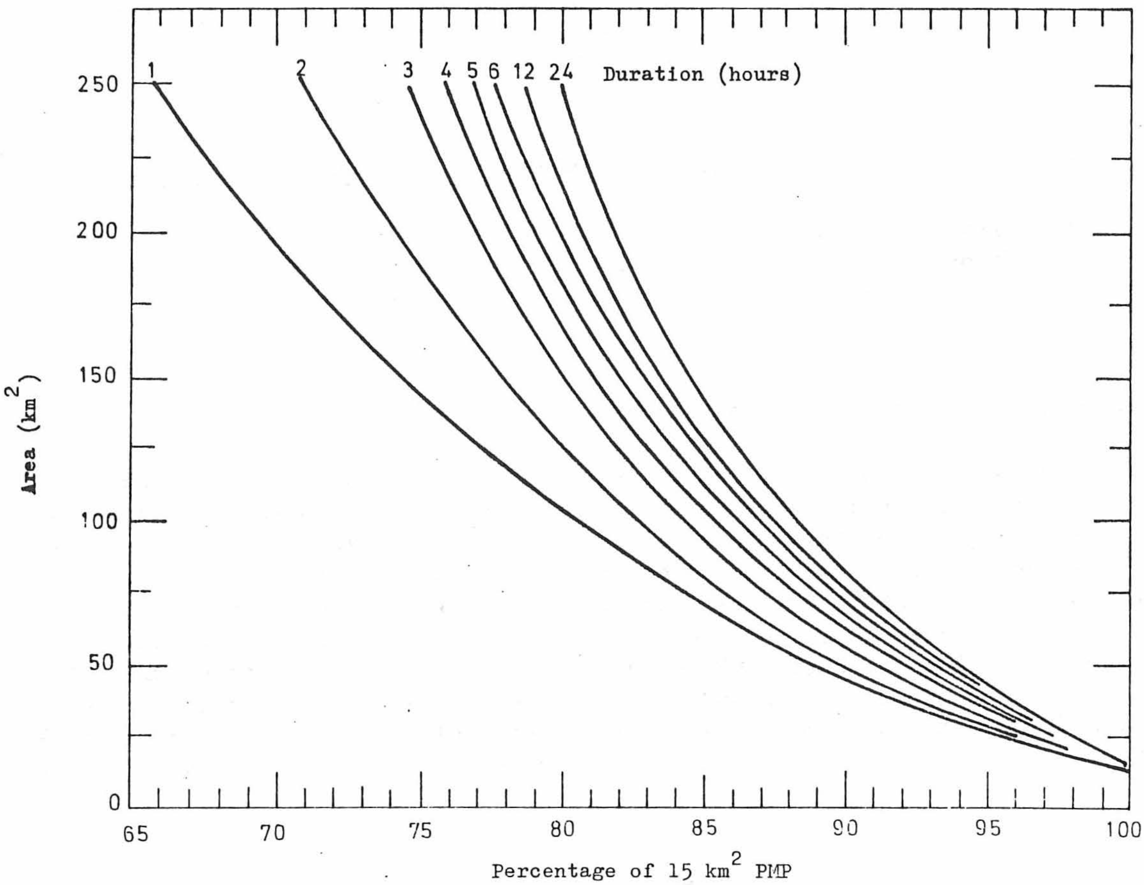


Figure 5.15 - PMP depth-area curve for small basins, Tennessee river basin

5.3.3.8 PMP for specific basins

PMP for specific basins is estimated as follows.

Step 1. Outline the basin on Figure 5.13, and determine mean 6-hour 15 km^2 PMP for the basin.

Step 2. Use Figure 5.14 to obtain PMP for durations up to 24 hours.

Step 3. Use Figure 5.15 to adjust 15 km^2 PMP for basin size.

Step 4. Construct a smooth enveloping depth-duration curve from data obtained in step 3, and determine 1-hour increments for the maximum six hours and 6-hourly increments for the remaining 18 hours.

Step 5. Suggest critical time sequences (section 5.3.3.7), such as: (a) hourly increments in maximum 6-hour period: 6, 5, 4, 3, 1, 2, where 1 refers to maximum 1-hour increment, and (b) 6-hourly increments in 24-hour storm: 4, 2, 1, 3, where 1 now refers to maximum 6-hour increment.

5.3.4 PMP for drainages from 250 to 8 000 km^2 in the Tennessee river basin

The discussion which follows refers only to the Tennessee river basin above Chattanooga, Tennessee /5/. The topography and moisture sources were discussed above, and topographic classifications are shown in Figure 5.8.

5.3.4.1 Derivation of non-orographic PMP

PMP was derived in the manner described in section 3.4.2. Storms for the eastern part of the country were maximized in place and enveloping isohyets constructed, thus applying an implicit transposition. PMP maps like that of Figure 3.20 were constructed for a number of basin sizes and durations, with isohyets not only enveloping the data on each chart but also showing smooth progression with varying basin size and duration. Values read from these charts for the location of Knoxville, Tennessee, were used to develop the basic PMP depth-area-duration relations of Figure 5.16. The 24-hour 2 500 km^2 chart (not shown) was converted to percentages of the value at Knoxville (Figure 5.17). Multiplication of the depth-area-duration values of Figure 5.16 by the percentages of Figure 5.17 yielded non-orographic PMP at various locations in the basin.

5.3.4.2 Orographic influences on PMP

Four indicators of orographic influence on precipitation were developed. These are summarized in this section. The first three were used to develop relationships already described.

Mean annual precipitation was one indicator. A hypothetical mean annual non-orographic precipitation map (not shown) was constructed by eliminating the influence of the Appalachian Chain by smooth extrapolation of isolines of mean annual precipitation from surrounding non-orographic regions. This map supports the generalized PMP percentile lines of Figure 5.17.

Charts of 2-year 24-hour rainfalls at some 600 stations in and near the basin and of extreme monthly rains were used also to assess orographic effects.

Another indicator of orographic influence was the comparison of the small-basin PMP chart of Figure 5.13 with the chart (not shown) reconstructed under the assumption that the smooth classification applied to the entire basin. Non-orographic PMP depth-area-duration values (Figure 5.16) are adjusted by the ratio of PMP index chart values (Figure 5.13) to 6-hour smooth PMP (Figure 5.9) adjusted for basin location (Figure 5.12).

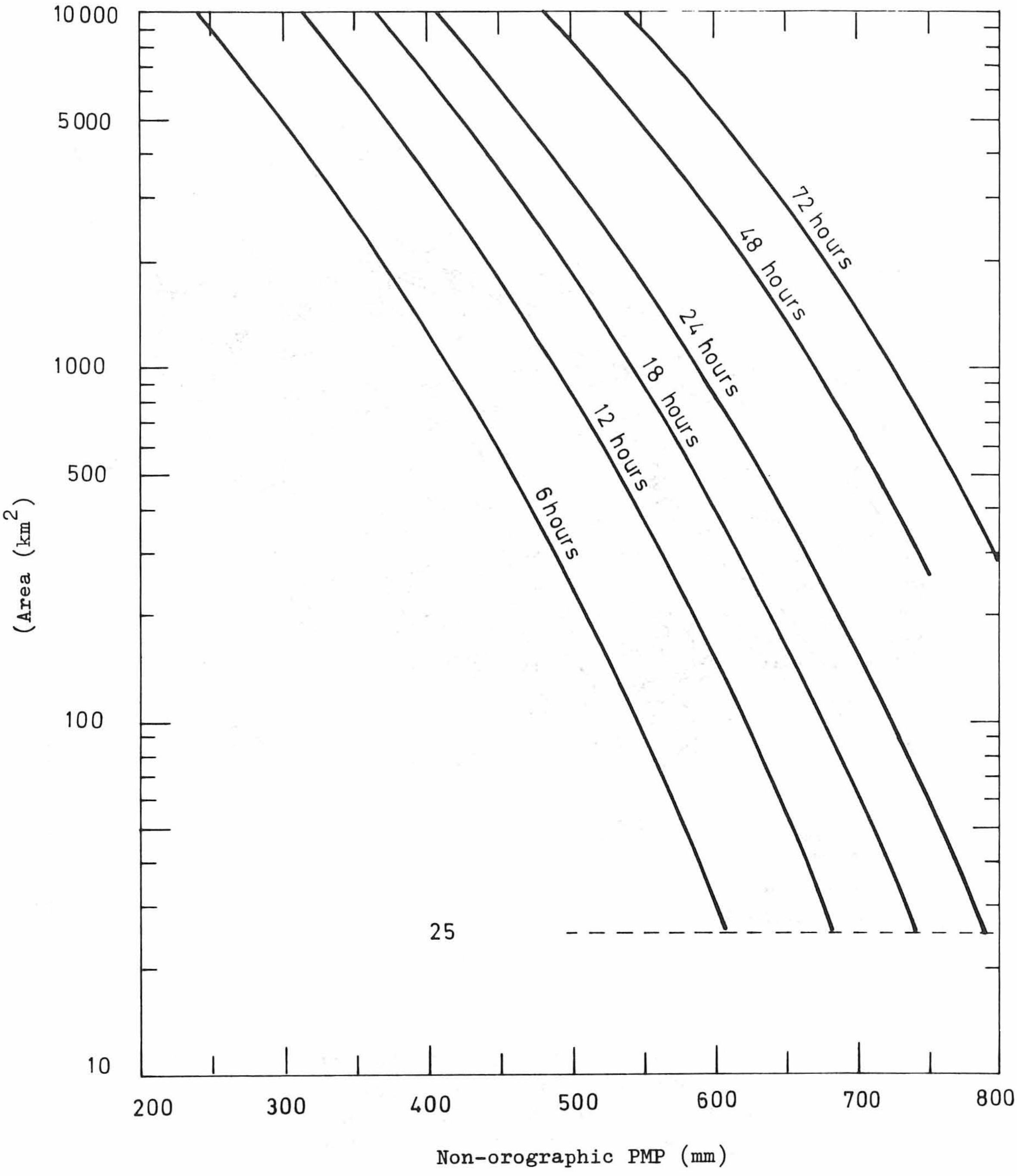


Figure 5.16 - Non-orographic PMP at Knoxville, Tennessee

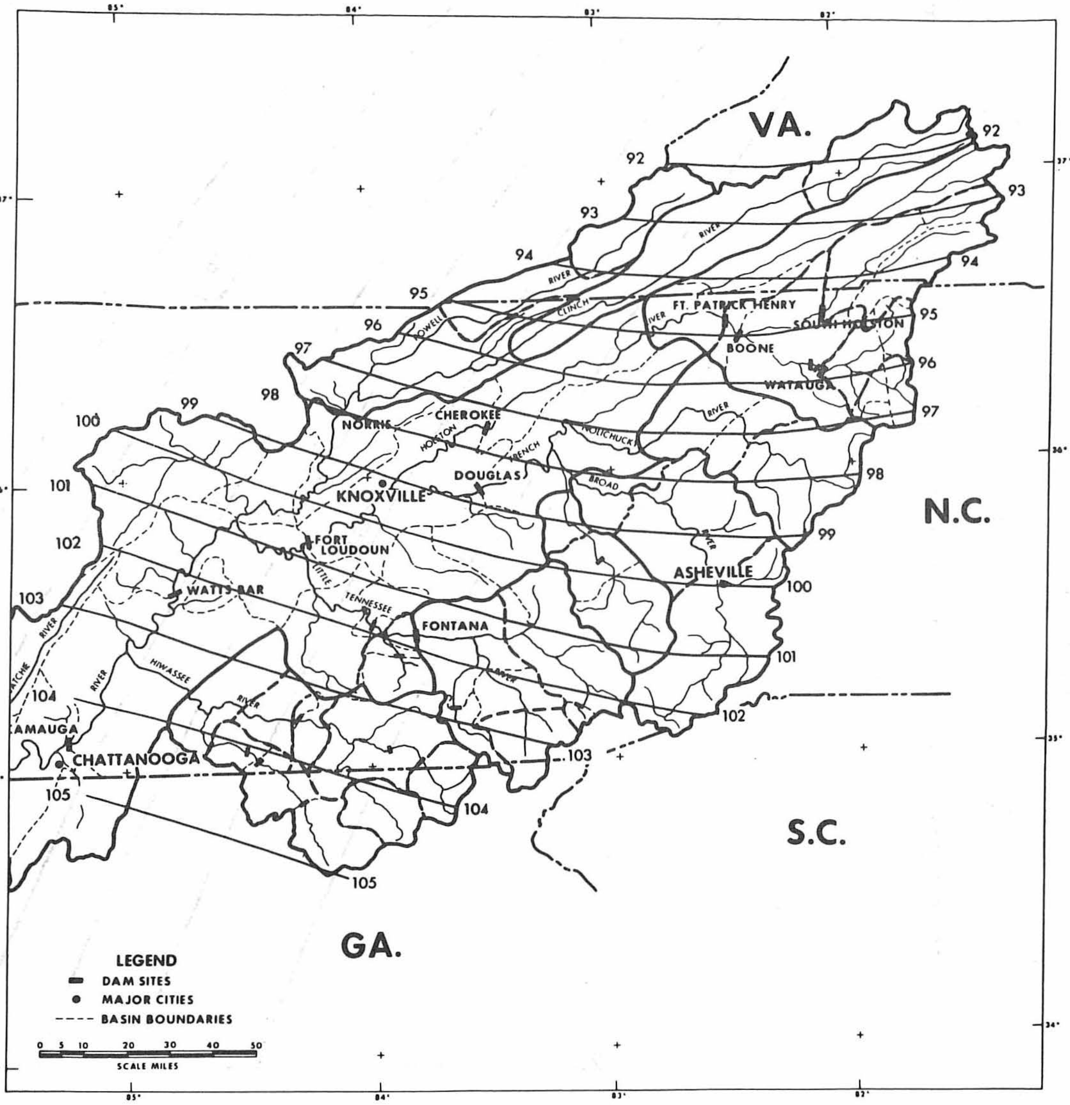


Figure 5.17 - 24-hour 2 500 km^2 PMP percentiles of Knoxville Airport value. (Meteorological observations made at airport, about ten miles south of Knoxville)

The optimum inflow direction for heavy rains was another index to orographic effect. Over a basin of no more than about 250 km^2, it is presumed that the optimum wind direction for unobstructed inflow of moist air and for accentuation of lift by ground slope prevails during the PMP storm. In larger basins, the optimum direction for precipitation may differ from one part of the basin to another because of varying intensification by principal slopes. The wind direction most critical for the basin

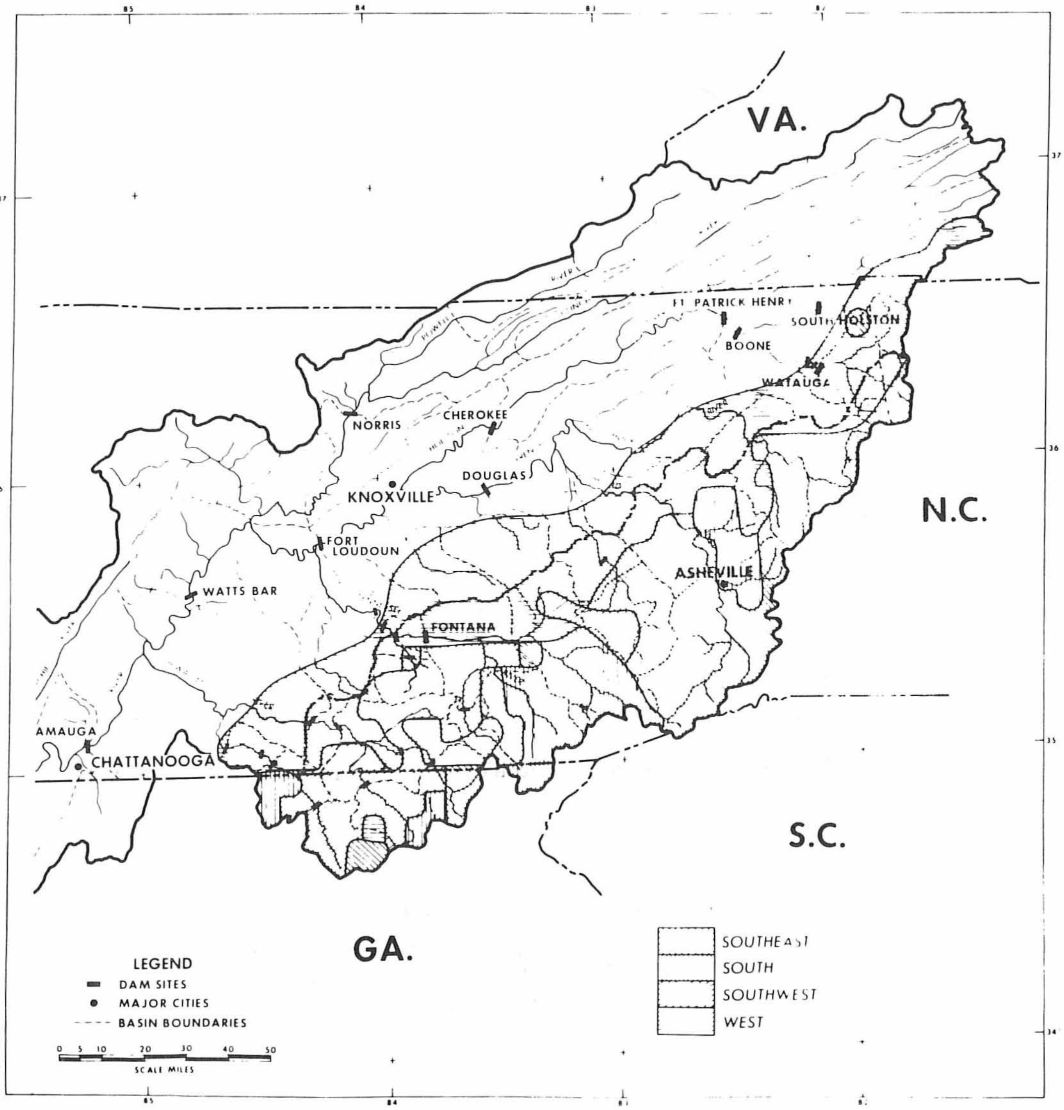


Figure 5.18 - Optimum wind directions for heavy rains

as a whole is defined as the direction that is most favourable over the largest portion of the basin. Figure 5.18 shows the optimum moisture-inflow directions for local areas. The largest percentage of a problem basin with the same optimum wind direction is determined from Figure 5.18. The orographic intensification factor is related to this percentage value by Figure 5.19, which was developed empirically after a number of PMP estimates for specific basins had been made.

The entire procedure for estimating PMP for specific basins is outlined in section 5.3.4.4.

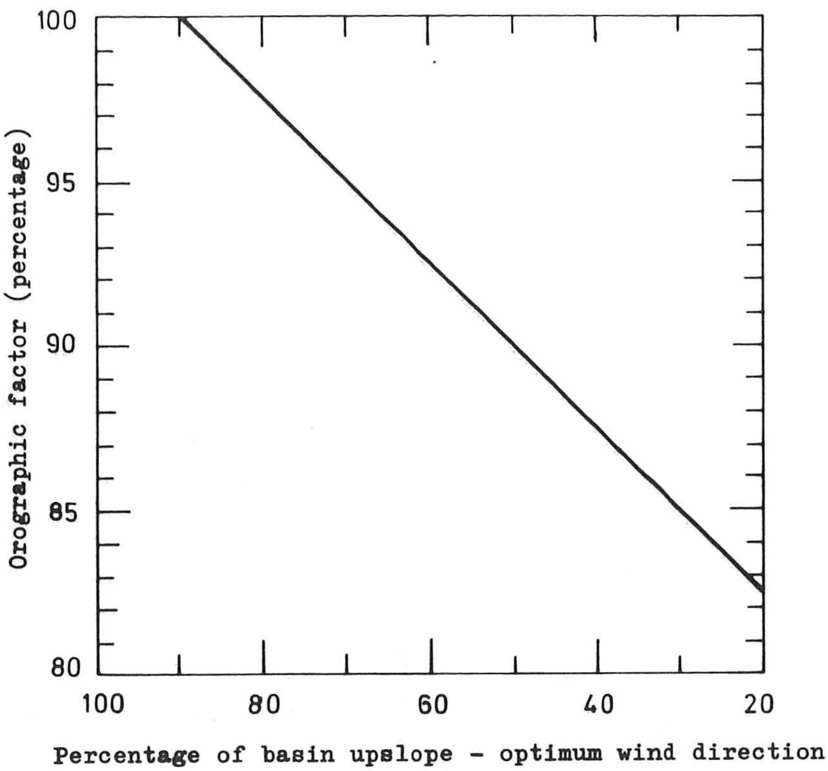


Figure 5.19 - Orographic adjustment chart for south-eastern mountainous portion of Tennessee river basin above Chattanooga, Tennessee

5.3.4.3 Areal and time distribution

The relationships described above yield the volume of PMP for specified sizes of area and for various durations. Geographic distribution of PMP within problem basins is determined by developing an idealized or typical representative storm isohyetal pattern and providing nomograms for obtaining isohyetal values. The procedure was described in section 3.4.2.5. Critical sequences of 6- and 24-hour rainfall increments may be arranged as described in section 3.4.2.6.

5.3.4.4 PMP for specific basins

For the relatively smooth north-western portion of the basin (unhatched regions of Figure 5.18), PMP estimates (see cautionary remarks, section 5.4) are obtained from the basic PMP at Knoxville (Figure 5.16) and the regional adjustment (Figure 5.17). The stepwise procedure follows.

Step 1. From Figure 5.16, obtain 6-, 12-, 18-, 24-, 48- and 72-hour values of non-orographic PMP for the basin size.

Step 2. Obtain percentage adjustment indicated in Figure 5.17 for the centre of the problem basin, and use it to multiply values obtained in step 1.

Step 3. Construct a smooth enveloping depth-duration curve from the adjusted values of step 2, and obtain 6-hour increments for the 72-hour PMP.

The procedure for estimating PMP (see cautionary remarks, section 5.4) in the mountainous south-eastern region (hatched in Figure 5.18) is more complicated. After the basic PMP (Figure 5.16) is adjusted regionally (Figure 5.17): (a) multiply by ratio of basin average 6-hour 15 km^2 PMP to basic smooth 6-hour PMP (635 mm, Figure 5.9) adjusted for the basin location (Figure 5.12); and (b) adjust the result for percentage of basin exposed to optimum wind direction (Figures 5.18 and 5.19).

The required steps may be followed more easily if it is assumed that PMP is being estimated for a hypothetical circular 800 km^2 basin centred at Fontana, Tennessee, with the results shown in Table 5.1.

Step 1. From Figure 5.16, obtain 6-, 12-, 18-, 24-, 48 and 72-hour values of PMP for the basin size. Enter on line A.

Step 2. Determine the location adjustment factor for the centre of the basin from Figure 5.17. Enter on line B.

Step 3. Multiply values of line A by those on line B to obtain geographically adjusted PMP values. Enter on line C.

Step 4. Lay out basin outline on Figure 5.13, and determine basin average 6-hour 15 km^2 PMP. (Assume that this value for the example basin is 30.0 in, or 762 mm.) Enter on line D under 6 hours.

Step 5. Obtain the non-orographic 6-hour 15 km^2 PMP from the smooth curve of Figure 5.9. The value is 635 mm, and applies to the 100 per cent line of Figure 5.12. Multiply the value by the percentage indicated for the location of the basin centre. (This percentage is 96 for the example basin.) Enter the product on line E under 6 hours.

Step 6. Divide value on line D by that on line E to obtain the unadjusted orographic factor. Enter on line F.

Step 7. Use Figure 5.18 to determine largest percentage of basin having a common optimum wind direction. (Assume that it is 60 per cent for the example basin). Enter on line G.

Step 8. Enter Figure 5.19 with percentage value from line G, and read corresponding orographic factor percentage. Enter on line H.

Table 5.1 - Sample computation of PMP for hypothetical 800 km^2 basin centred at Fontana, Tennessee

Line	Item and source	Duration (hours)					
		6	12	18	24	48	72
A	Non-orographic PMP (mm) at Knoxville for 800 km^2 (Figure 5.16) ...	430	505	560	603	685	740
B	Adjustment for basin location, in percentage (Figure 5.17)........	102	102	102	102	102	102
C	Non-orographic PMP (mm) for basin (line A × line B).............	439	515	571	615	699	755
D	Mean 6-hour 15 km^2 PMP (mm) for basin (Figure 5.13)...............	762					
E	Non-orographic 6-hour 15 km^2 PMP (635 mm) from smooth curve of Figure 5.9 multiplied by 0.96 from Figure 5.12...........	610					
F	Unadjusted orographic factor (line D ÷ line E)....................	1.25	1.25	1.25	1.25	1.25	1.25
G	Percentage of basin exposed to optimum wind direction (Figure 5.18)..	60	60	60	60	60	60
H	Orographic factor percentage (Figure 5.19).......................	92	92	92	92	92	92
I	Net orographic factor (line F × line H).........................	1.15	1.15	1.15	1.15	1.15	1.15
J	Basin PMP, in mm, (line C × line I)..........................	505	592	657	707	804	868

Step 9. Multiply values on line F by those on line H to obtain net orographic factor. Enter on line I.

Step 10. Multiply values of line C by those on line I to obtain PMP values for the example basin. Enter on line J.

Step 11. Construct a smooth enveloping depth-duration curve from the values of line J, and obtain 6-hour increments for the 72-hour PMP.

5.3.5 PMP for the Lower Mekong river basin in south-east Asia

Generalized estimates of PMP were made [9] for drainages from 5 000 to 25 000 km^2 in the Mekong river basin south of the Chinese border at about 22°N latitude (Figure 5.20). This part of the basin is referred to generally as the Lower Mekong. The procedure used in making these estimates provides an example of how data from one part of the world may be used to estimate PMP for a region with inadequate data.

5.3.5.1 Mean seasonal precipitation map

A rough approximation of regional variation of rainfall potential may be gained from mean seasonal or annual precipitation maps. A map of mean rainfall was developed for the May-September season, the south-west monsoon period, which produces most of the annual rainfall for much of the Lower Mekong. Rainfall observations provided the primary basis for the seasonal map. As usual, few observations were available for mountainous areas.

Where data are severely limited in mountainous regions, as was the case in the Mekong basin, determination of detailed effects of topography on precipitation is a hopeless task. In such situations, relations based on extensive smoothing of topography are the best that can be developed. Figure 5.21 shows the generalized topography of the Mekong drainage and the locations of precipitation stations.

Topographic effects on seasonal rainfall distribution were assessed on the basis of the limited data and on past experience gained from study of these effects in regions with adequate data. Comparisons of mean rainfalls at a few pairs of stations in the Mekong river basin, critically selected to reflect different topographic effects within each pair, provided guidance. These comparisons, plus experience, led to the following guidelines: (1) for mountain slopes facing south to west, with no nearby mountain barriers to moisture inflow, rainfall approximately doubles in the first 1 000 m rise in elevation. Except for extremely steep slopes extending to high elevations no further increase was indicated. (2) Upslopes near the coast, outside the basin but bounding it, produce spillover rainfall over limited areas in the basin. (3) Sheltered areas immediately to the lee of mountain barriers receive about half the rainfall observed upwind of the barriers.

The above guidelines, plus general guidance from some streamflow data, supplemented observed rainfall data in the construction of the mean May-September rainfall map (Figure 5.22). Mean rainfall maps for August and September, the wettest months, were constructed in a similar fashion.

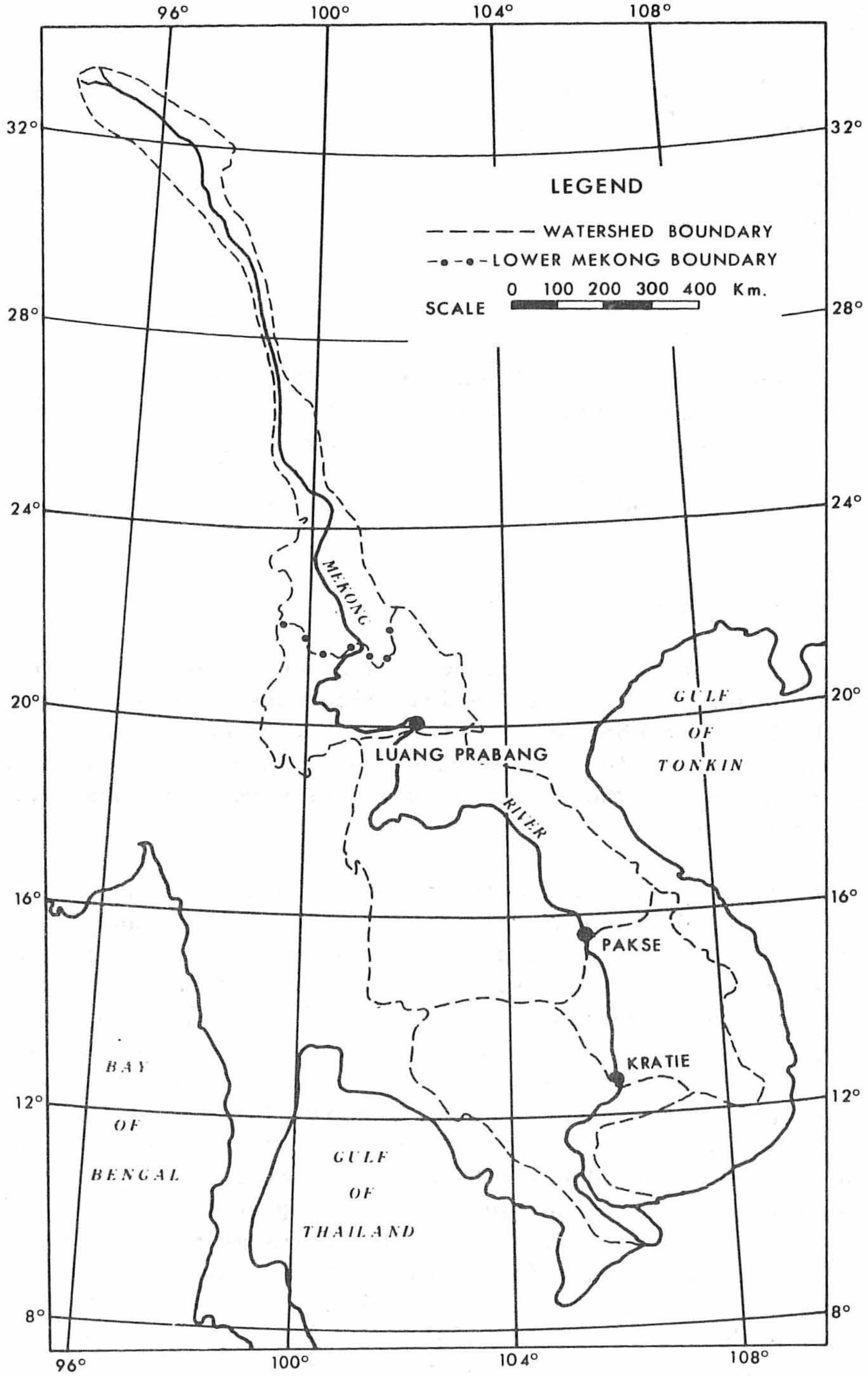


Figure 5.20 - Mekong river basin and sub-basins

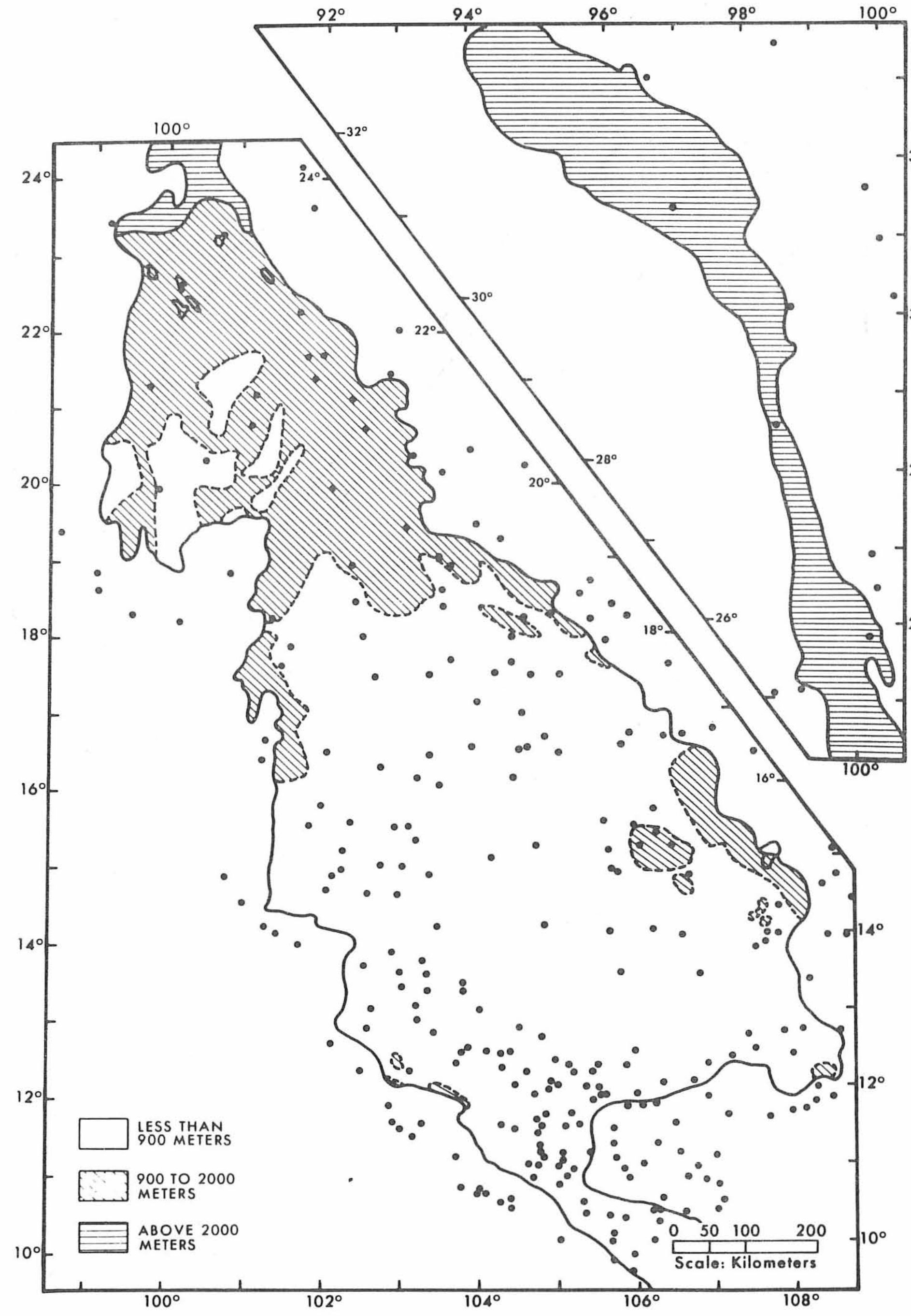


Figure 5.21 - Generalized topography of Mekong river basin with precipitation stations

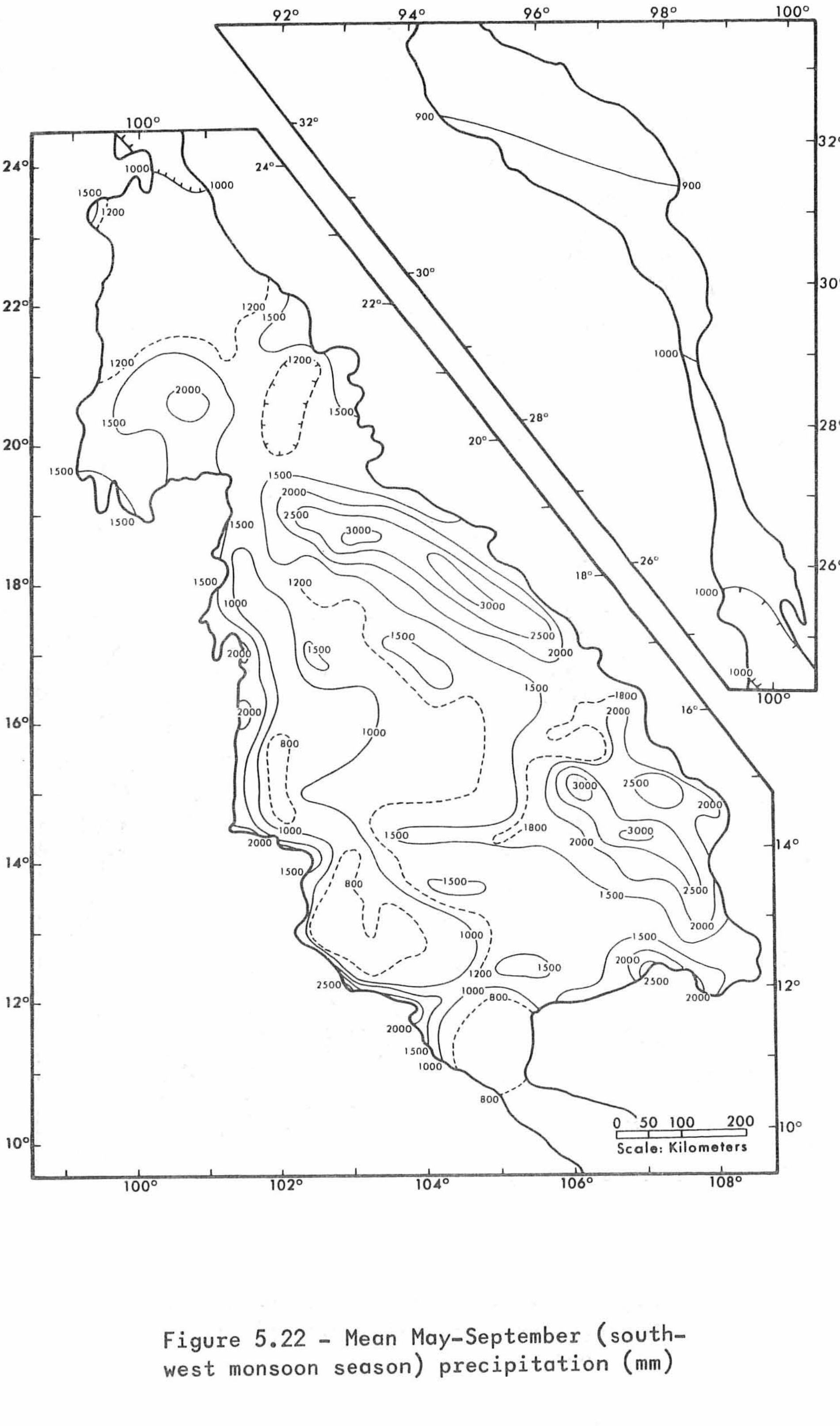


Figure 5.22 - Mean May-September (south-west monsoon season) precipitation (mm)

5.3.5.2 The typhoon as a PMP prototype

Typhoons are the most important producers of heavy rains for durations of several days in the Lower Mekong for the range of basin sizes considered in this example. Such storms, approaching the Mekong basin from the east, produce the heaviest general rainfalls in the basin in spite of mountain barriers between the coast and the eastern border of the basin. Rainfalls from typhoon Vae (21-22 October 1952), in the southern portion of the Lower Mekong basin and Tilda (21-25 September 1964), near the middle, are foremost examples. Large-area rainfalls from these storms, after adjustment as described below, approximate greatest values from tropical storms throughout the world.

With the idea of adapting the more abundant depth-area-duration rainfall data from tropical storms along the United States coast to the Mekong drainage, the massiveness (size and intensity), speed of movement, and other features of tropical storms affecting the two regions were compared. Also compared were average maximum 1-day point rainfalls from tropical storms in the United States and in the Pacific Ocean, including the Vietnam coast. Values along the Vietnam coast were about 20 per cent greater, but the excess was attributed to topographic influences absent in the coastal regions of south-eastern United States. The comparisons suggested that non-orographic tropical storm rainfall potential was about the same for the two regions.

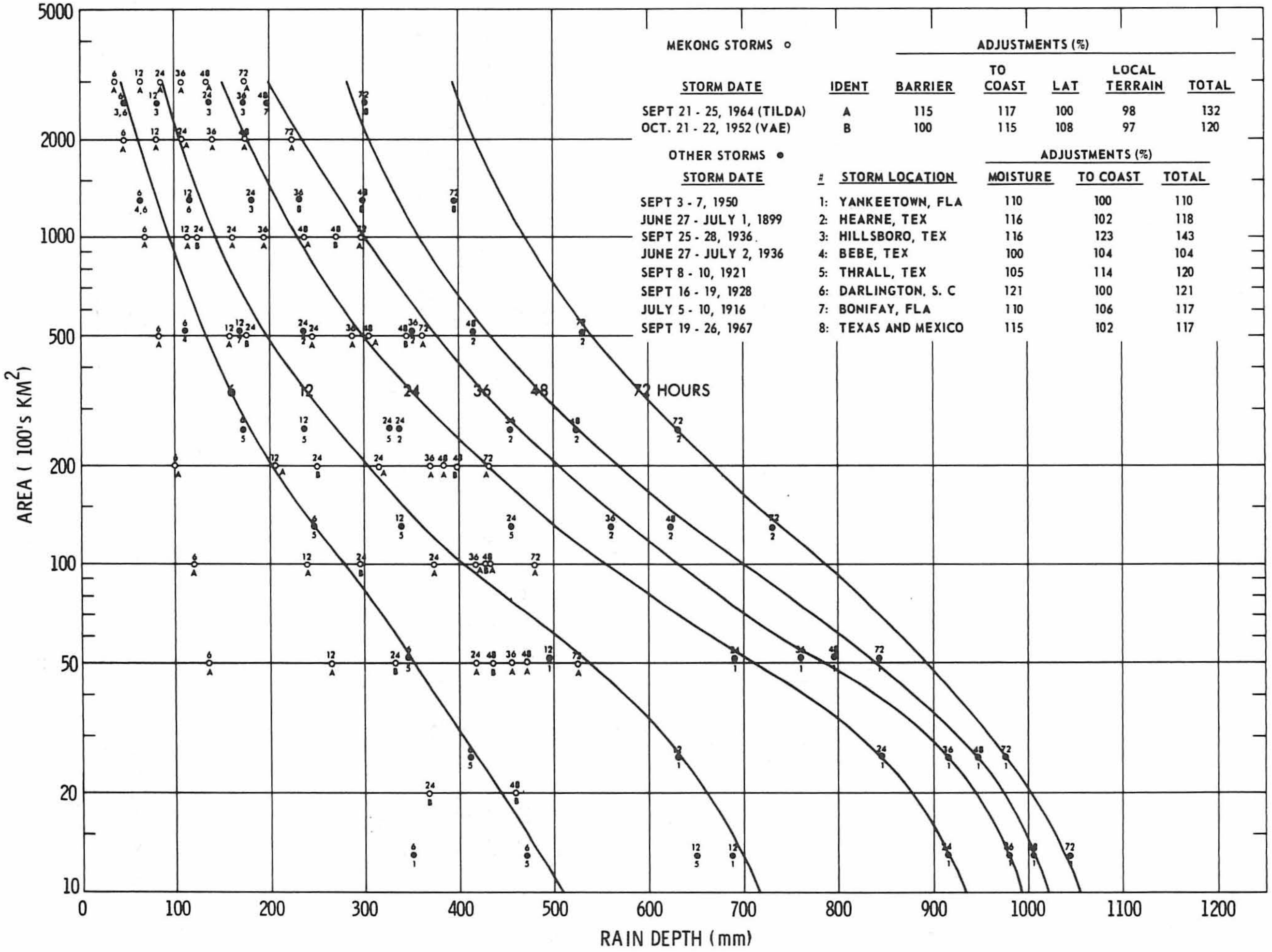
5.3.5.3 Adjustment of U.S. tropical storm rainfalls

Two adjustments were made to the U.S. tropical storm depth-area-duration (DAD) data to make them applicable to the Vietnam coast. First, the storm data were moisture maximized for a persisting 12-hour dew point of 26°C, the highest value for U.S. coastal regions affected by tropical storms. Second, an adjustment was made for the decrease of tropical storm rainfall with distance inland. This adjustment is discussed in the following section. The adjusted data and enveloping DAD curves are shown in Figure 5.23. The DAD curves were considered to represent non-orographic PMP just off the Vietnam coast.

5.3.5.4 Adjustment of Vietnam tropical storm rainfalls

Since the non-orographic PMP DAD curves of Figure 5.23 applied only to the Vietnam coast, the indicated values had to be modified for occurrence in the Mekong basin. The following adjustments were thus required for distance inland, moisture source, latitude, moisture-inflow barriers and basin topography.

Adjustments for distance inland and moisture source The general decrease in tropical storm rainfall with distance inland previously developed in another study [4] was considered applicable to south-east Asia. Approximately 60 U.S. storms in mostly non-orographic regions were used. Figure 5.24 shows the adjustment for the Lower Mekong in percentages of the PMP values off the coast.



MEKONG STORMS ○

STORM DATE	IDENT	ADJUSTMENTS (%) BARRIER	TO COAST	LAT	LOCAL TERRAIN	TOTAL
SEPT 21 - 25, 1964 (TILDA)	A	115	117	100	98	132
OCT. 21 - 22, 1952 (VAE)	B	100	115	108	97	120

OTHER STORMS ●

STORM DATE	#	STORM LOCATION	ADJUSTMENTS (%) MOISTURE	TO COAST	TOTAL
SEPT 3 - 7, 1950	1:	YANKEETOWN, FLA	110	100	110
JUNE 27 - JULY 1, 1899	2:	HEARNE, TEX	116	102	118
SEPT 25 - 28, 1936	3:	HILLSBORO, TEX	116	123	143
JUNE 27 - JULY 2, 1936	4:	BEBE, TEX	100	104	104
SEPT 8 - 10, 1921	5:	THRALL, TEX	105	114	120
SEPT 16 - 19, 1928	6:	DARLINGTON, S. C	121	100	121
JULY 5 - 10, 1916	7:	BONIFAY, FLA	110	106	117
SEPT 19 - 26, 1967	8:	TEXAS AND MEXICO	115	102	117

Figure 5.23 - Depth-area-duration curves of probable maximum precipitation on Vietnam coast

While typhoons approach the Mekong basin from an easterly direction, the wind circulation brings in moisture from southerly and easterly directions. The few analyzed storms in the basin clearly demonstrate multiple sources of moisture. Thus, the distance inland adjustment (Figure 5.24) incorporates a weighting of the generalized decrease for moisture-inflow direction for the region south of 17°N. A weight of one-third was given to distance inland from the south coast and two-thirds to distance from the south-east to east coasts.

Latitude Typhoon rainfall potential must decrease to about zero near the equator. The literature reports few cases south of 10°N. It was assumed typhoons could maintain full intensity as far south as 15°N. The need for maintaining a high typhoon rainfall potential in southerly reaches of the basin is supported by the October 1952 storm that occurred in the basin near 12°N. The adopted adjustment is shown in Figure 5.25.

Barrier adjustment In addition to the generalized decrease in rainfall with distance in non-orographic regions, it was necessary to consider decrease within the basin due to moisture-inflow barriers. The decrease varies with height of barriers and their uniformity, i.e., whether continuous or with breaks, or passes. Moisture inflow from a southerly direction reduces the depleting effect of the eastern coastal mountains. The eastern barrier was therefore considered to reduce rainfall to the west by half the usual barrier reduction. Figure 5.26 shows the adopted adjustment applicable to coastal rainfall values.

Adjustment for basin topography Typhoon Tilda (September 1964), mentioned above, produced increased rainfall along south-west facing slopes in the basin. This is consistent with the assumption that moisture from southerly or south-westerly directions, with relatively low intervening inflow barriers, must be considered in assessing regional variations in PMP. As an aid in evaluating topographic effects for these inflow directions, ratios of high- to low-elevation mean May-September precipitation were used as primary indices. A bias in the mean seasonal precipitation map (Figure 5.22), resulting from more frequent precipitation at high elevations, precluded direct use of variations in seasonal precipitation as an indication of variations in a 3-day storm. Comparison of rainy day station values suggested an increase with elevation of about 60 per cent over that indicated by mean seasonal values for application to typhoon PMP.

Another adjustment of monsoon season rainfall ratios involved consistency with the one-half effectiveness adopted for the eastern barrier adjustment. This implied that south-west slopes were effective for only one-half the storm duration. The rainfall elevation relation thus becomes 30 per cent of that indicated on the map. A mean seasonal low-elevation rainfall value of 1 200 mm was used as a basic non-orographic value. Percentage increases for typhoon rainfall on windward slopes and decreases on lee regions as indicated by south-west monsoon season rainfall (Figure 5.22) are shown in Figure 5.27.

Combined adjustment Combination of the above adjustments (Figures 5.24 to 5.27) produced the combined adjustment chart of Figure 5.28, which relates to coastal Vietnam typhoon rainfall values equated to 100 per cent.

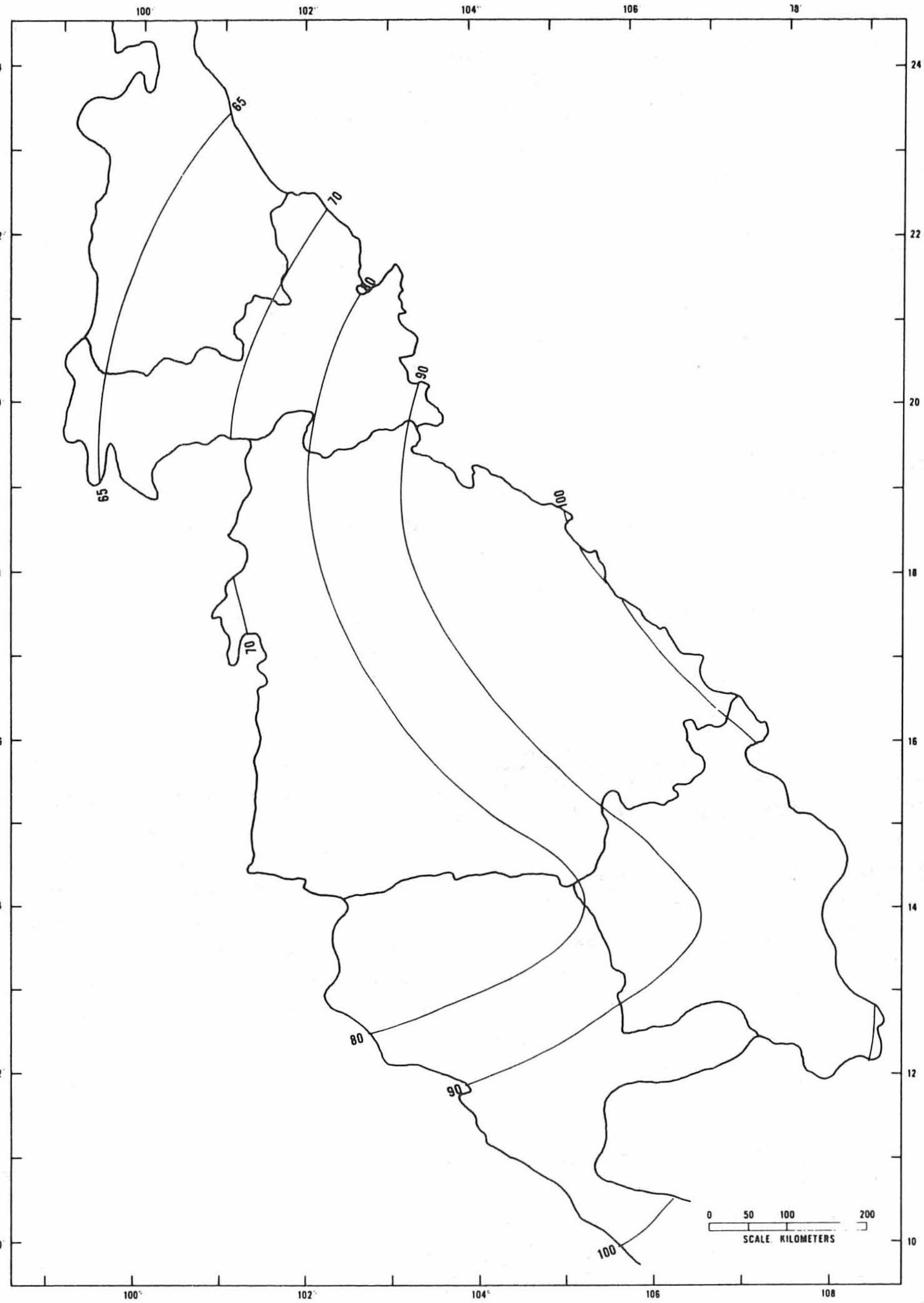


Figure 5.24 - Adjustment (percentage) of coastal typhoon rainfall for distance inland

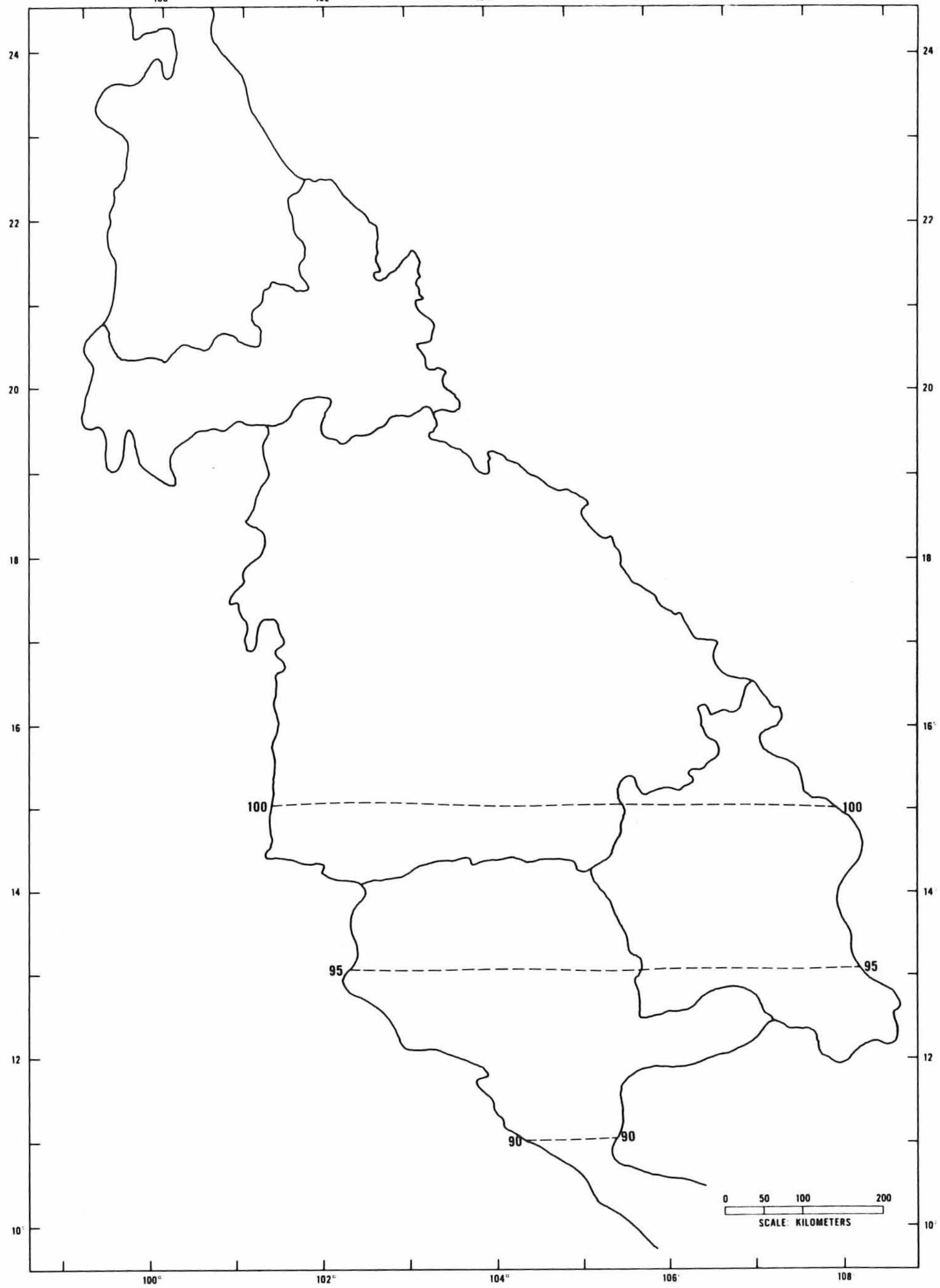


Figure 5.25 - Latitude adjustment of typhoon rainfall as percentage of values at 15°N

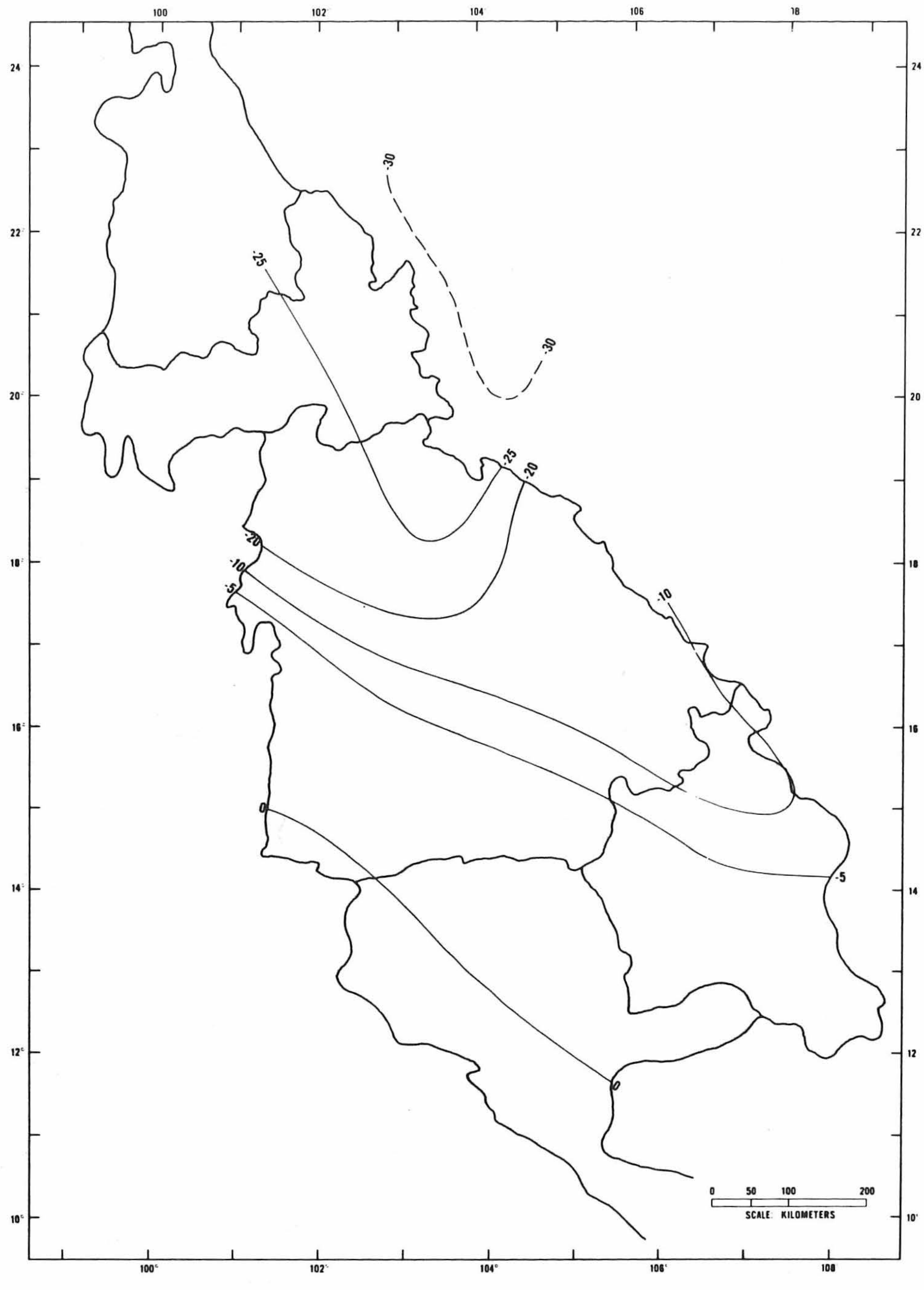


Figure 5.26 - Barrier adjustment of typhoon rainfall (percentage decrease)

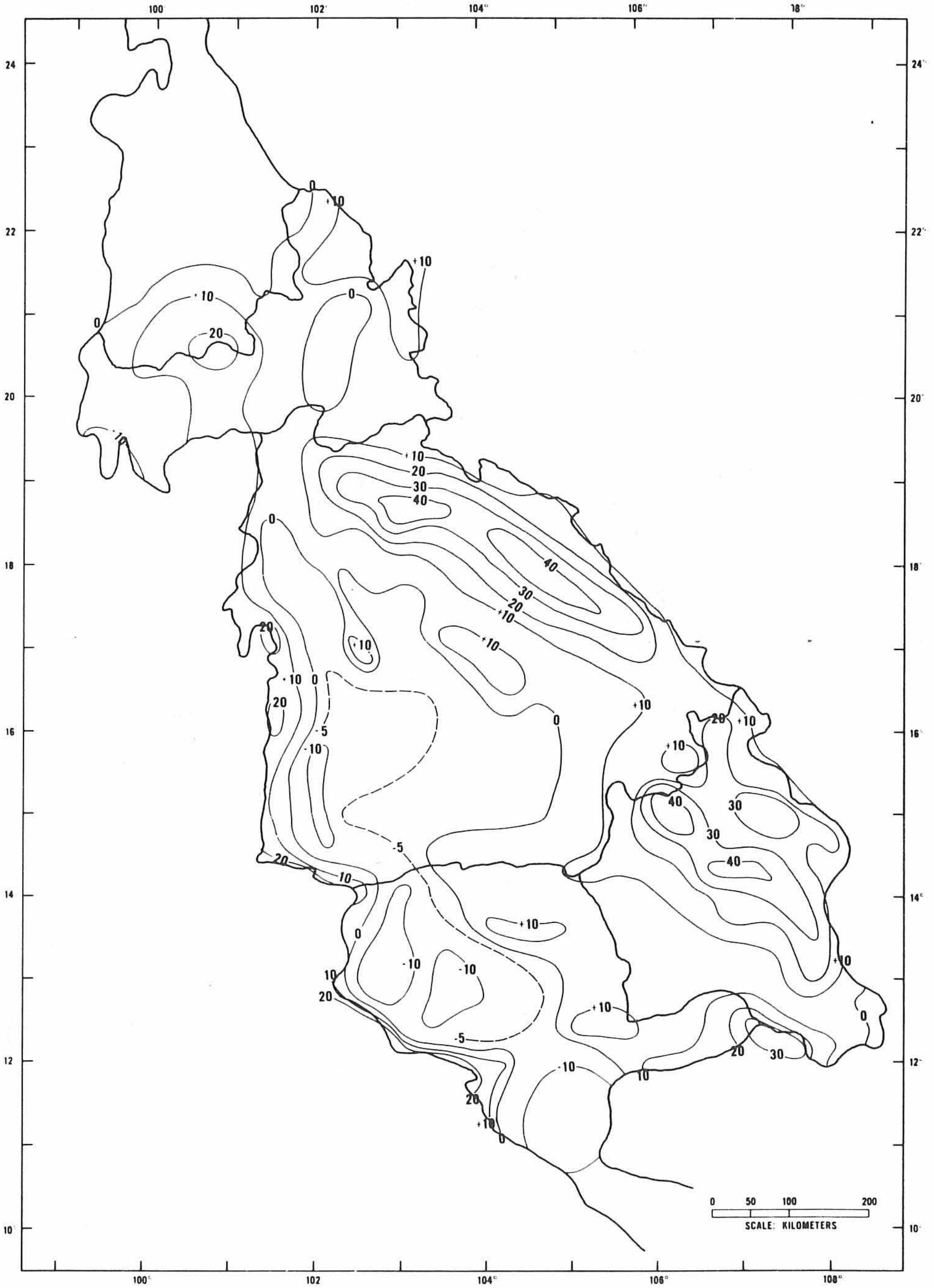


Figure 5.27 - Adjustment of typhoon rainfall for basin topography (percentage increase or decrease relative to low-elevation south-west monsoon rainfall over flat terrain)

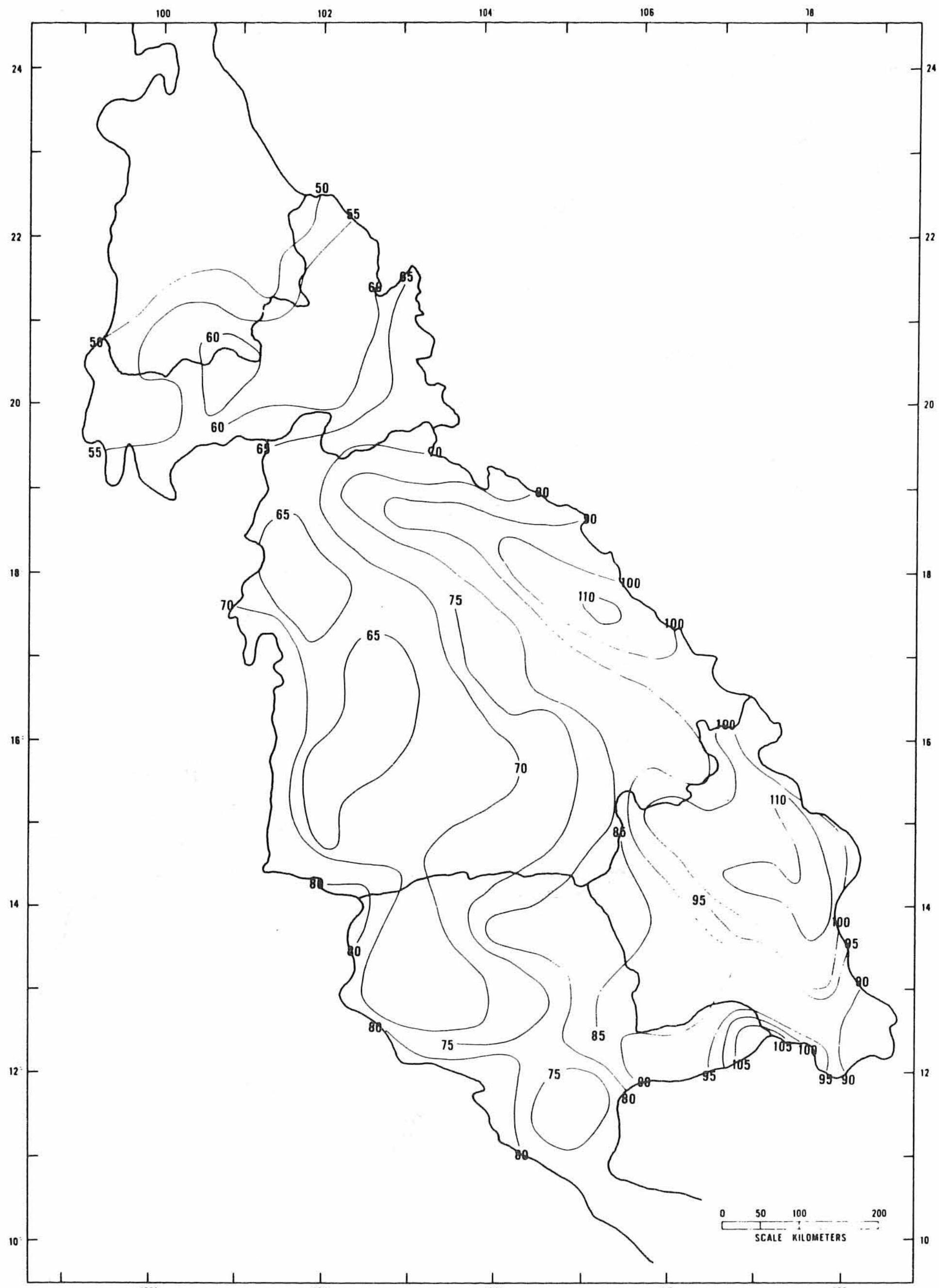


Figure 5.28 - Total adjustment (percentage) of coastal typhoon rainfall (combined adjustments of Figures 5.24 to 5.27)

5.3.5.5 Generalized estimates of PMP

The 24-hour 5 000 km^2 coastal PMP values of Figure 5.23 were multiplied by the combined adjustment percentages of Figure 5.28 to obtain the generalized PMP map of Figure 5.29. PMP values for basin sizes between 5 000 and 25 000 km^2 from Figure 5.23 were expressed as percentages of the 24-hour 5 000 km^2 PMP. These percentages were then used to construct the curves of Figure 5.30.

5.3.5.6 Time distribution

Examination of hourly records of intense rainfalls in the Mekong Basin showed various sequences of 6-hour increments during a storm period. Those associated with tropical storms, for example, Tilda of September 1964, had rain bursts lasting up to 30 hours with greatest intensities near the centre of the burst. Some stations reported double bursts with an intervening lull of 6 to 18 hours.

Strictly speaking, in order to maintain PMP magnitude no lulls can be allowed in a sequence of 6-hour rainfall increments during the PMP storm. In other words, the greatest, second greatest, etc., down to the twelfth greatest must be arranged in an ascending or descending order such that the highest increments always adjoin. Such a sequence is unrealistic, however, and that described in section 3.4.2.6 was recommended as essentially conforming to requirements for the 72-hour PMP storm.

5.3.5.7 Areal distribution

Isohyetal patterns for 6-hour rainfall increments in observed storms have various configurations. Some approach simple concentric circles or ellipses, while others are complicated, often with centres of high and low rainfall in close proximity to each other. An elliptical pattern, similar to that of Figure 3.26, was recommended for the four greatest 6-hour rainfall increments. Uniform areal distribution was recommended for the remaining 48 hours of the storm.

Within a 3-day period, the isohyetal centre of a major storm usually moves along the storm path. In the most extreme rainfalls, the storm may become almost stationary. It is therefore considered reasonable to have the isohyetal centre over the same location for a 24-hour period in the PMP storm.

Depth-area-duration relationships in the heaviest tropical storm rainfalls of the Mekong basin and the United States were used to establish isohyetal values for the selected pattern. Particular attention was given to maximum 6- and 24-hour rainfalls. For these durations, consistent depth-area curves were constructed for standard area sizes of 5, 10, 15 and 25 thousand km^2. With the 6- and 24-hour relations established, the second and third heaviest rainfall increments were computed proportional to PMP increments at standard size areas. The dashed curves of Figure 5.31 represent adopted depth-area relations for key basin sizes and durations. The solid curves are based on Figure 5.23. The storm depth-area curves and PMP depth-area-duration data were used to develop nomograms like that of Figure 5.32 for evaluating isohyetal value Such nomograms are derived by the procedure described in section 2.11.3, the only difference being that isohyetal values were converted into percentages of average rainfall enclosed by the respective isohyets and presented as a nomogram instead of in a table.

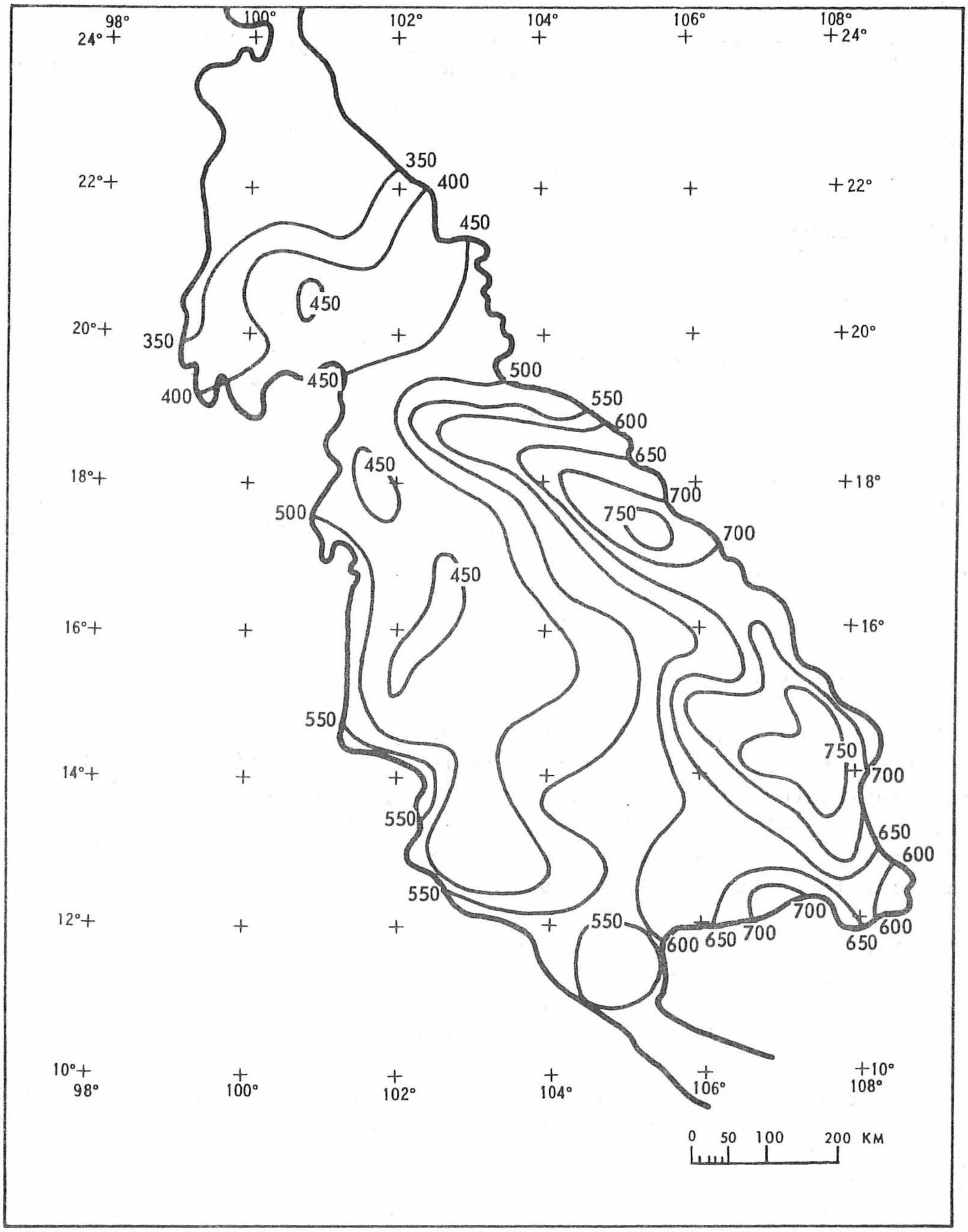


Figure 5.29 - Probable maximum precipitation for 24 hours over 5 000 km^2

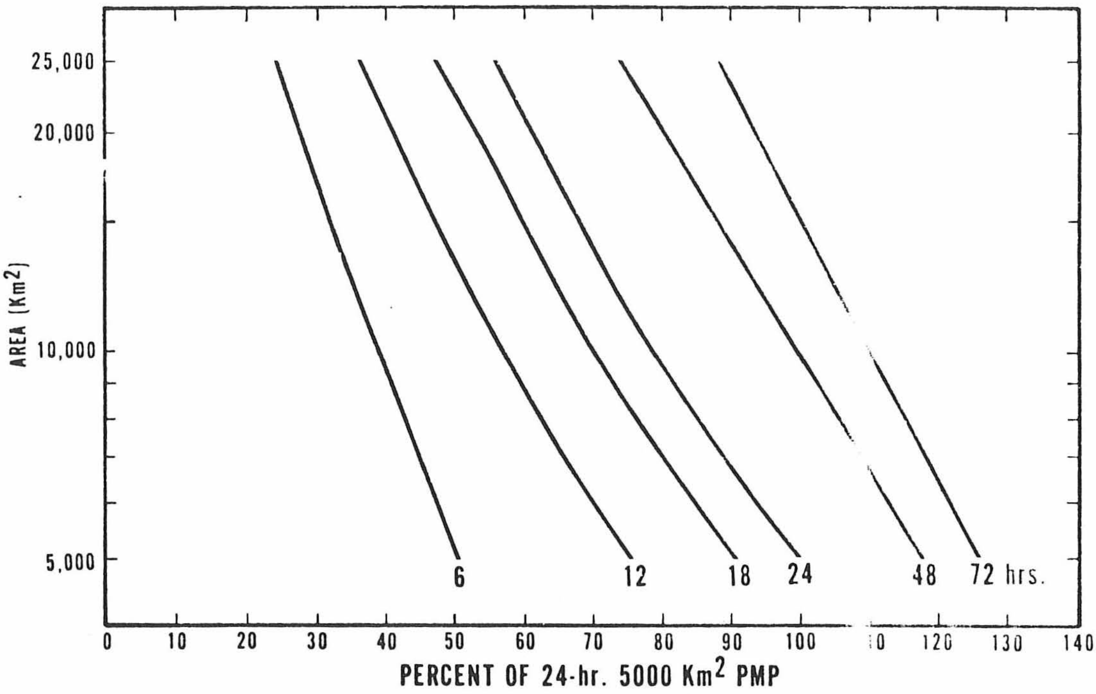


Figure 5.30 - Depth-area-duration values of PMP in per cent of 24-hour 5 000 km^2 PMP

5.3.5.8 PMP for specific basins

PMP for specific basins (see cautionary remarks, section 5.4) is estimated as follows.

Step 1. Lay out basin outline on Figure 5.29 and determine average 24-hour 5 000 km^2 PMP for the basin.

Step 2. From Figure 5.30, read percentages of 24-hour 5 000 km^2 PMP for 6, 12, 18, 24, 48 and 72 hours for the basin area.

Step 3. Multiply basin average 24-hour 5 000 km^2 PMP from step 1 by the percentages of step 2 to obtain basin PMP.

Step 4. Use data from step 3 to construct a smooth depth-duration curve, and read off 6-hour PMP increments for the entire 72-hour storm.

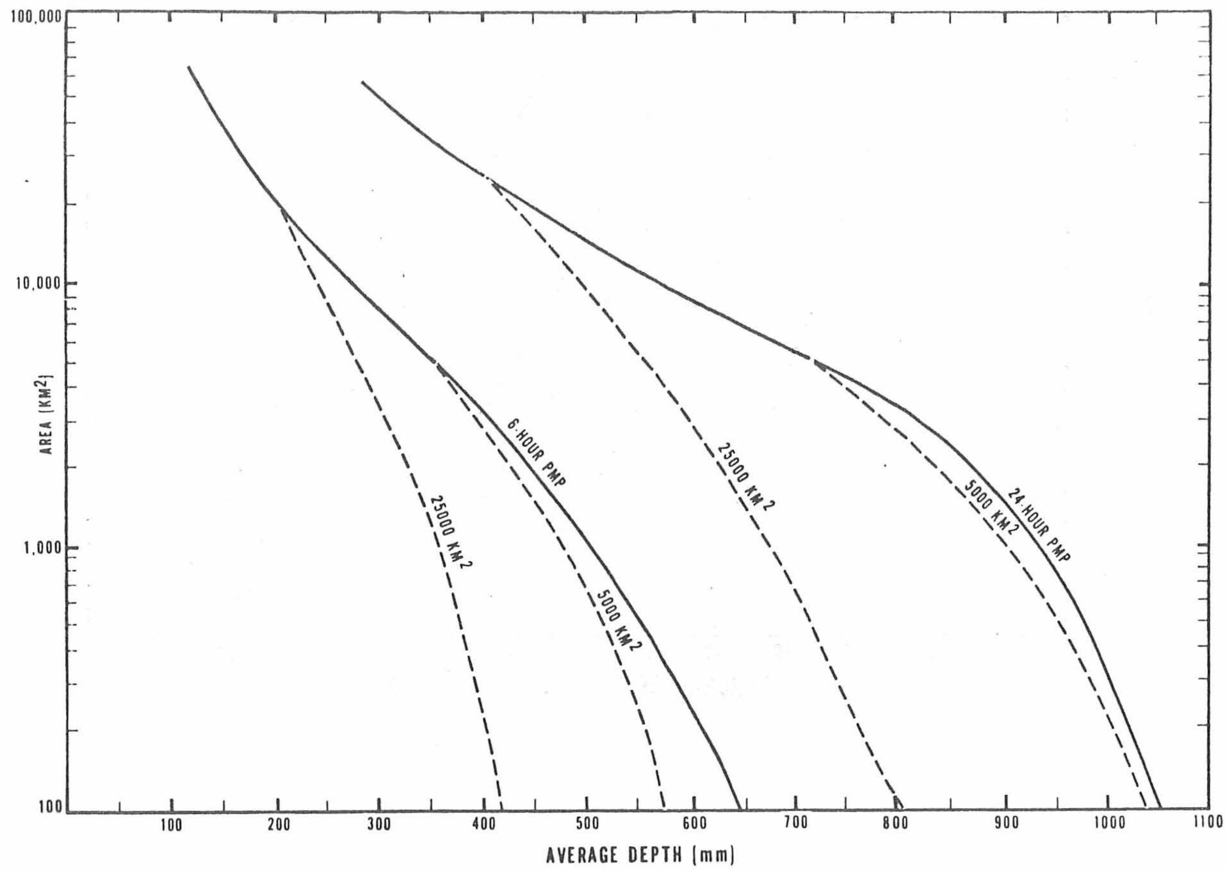


Figure 5.31 - PMP (solid lines) and key depth-area curves typical of major tropical storms

<u>Step 5</u>. Arrange 6- and 24-hour increments as described in section 5.3.5.6.

<u>Step 6</u>. Use selected elliptical isohyetal pattern (not shown) to distribute the four greatest 6-hour rainfall increments. Centre and orient pattern over the problem basin so as to obtain most critical runoff, which usually results with greatest rainfall volume within the basin. Enter Figure 5.32 with basin area, ana read percentage values for each isohyet, P to E, for the maximum 6-hour increment. Multiply the maximum 6-hour PMP increment of step 5 by these percentages to obtain isohyetal values in mm. Values for second, third and fourth PMP increments are obtained in a similar manner from similar nomograms (not shown).

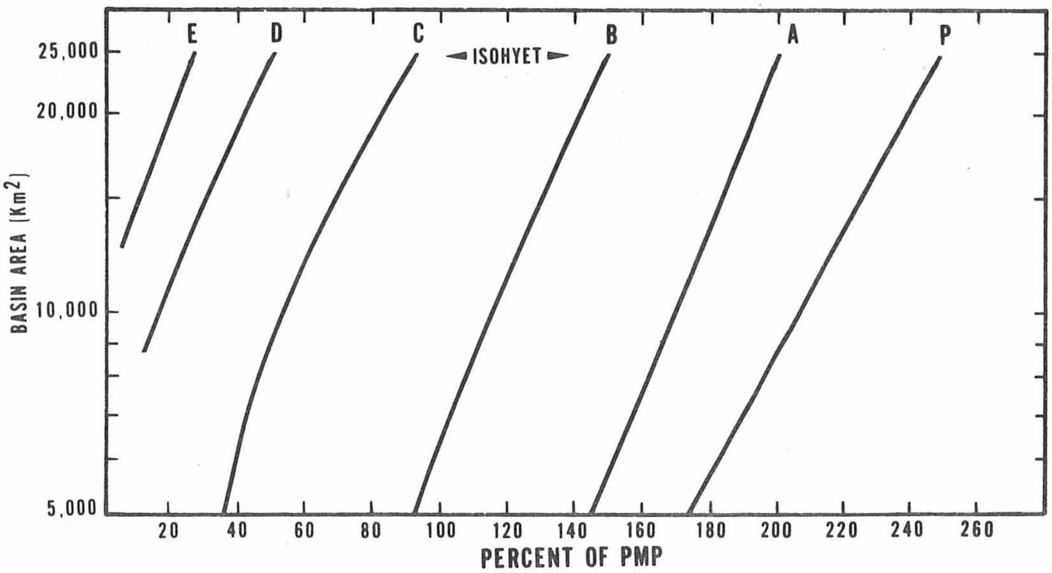


Figure 5.32 - Isohyetal values for maximum six-hour increment of PMP storm as percentage of average rainfall for area enclosed

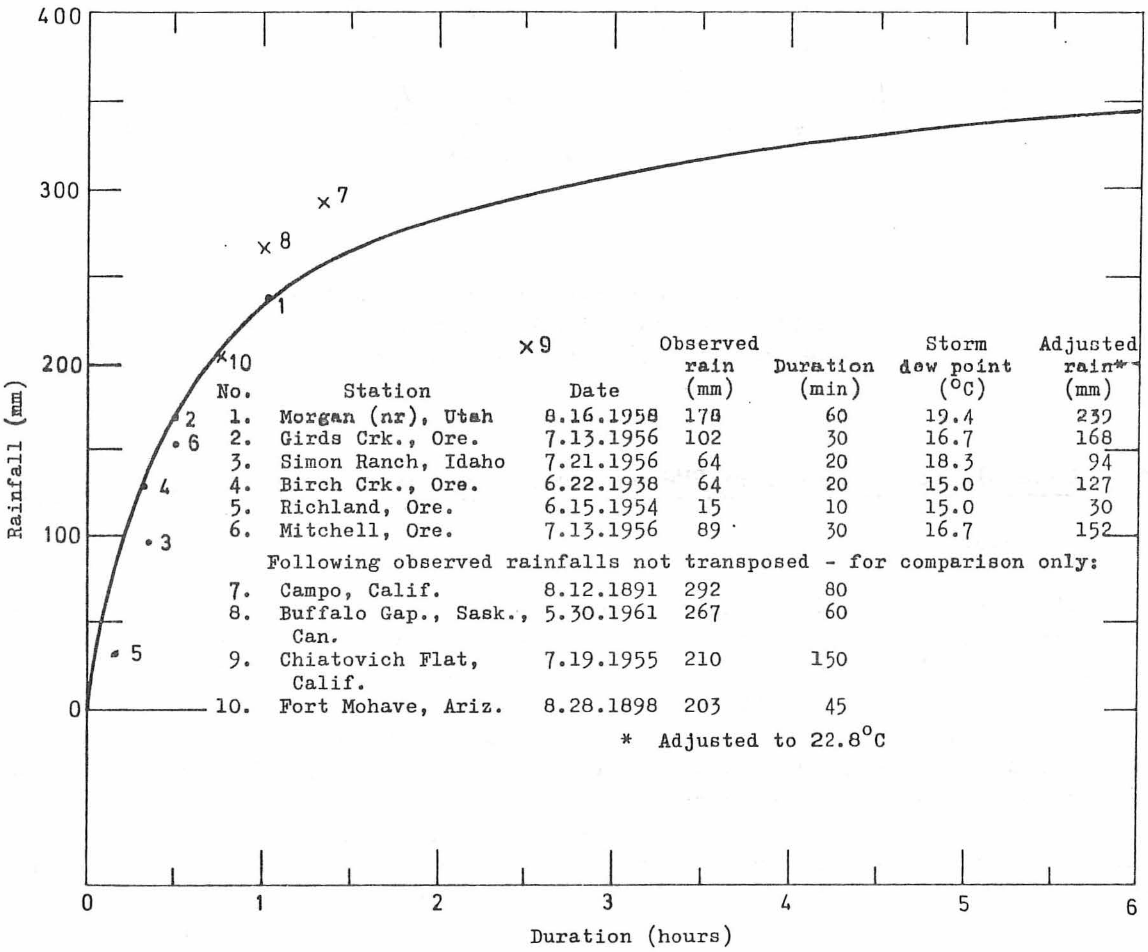
5.3.6 Generalized thunderstorm PMP estimates for north-western United States

5.3.6.1 Introduction

Thunderstorm rainfalls usually provide the maximum amounts for small areas, say up to about 1 000 km^2, and durations shorter than about 6 hours. Extreme observed values indicate less latitudinal variation within middle latitudes than do general storms. While severe thunderstorms are often associated with vigorous weather systems, some of those producing extreme rainfalls occur during periods of weak atmospheric circulation. For this reason, and because of their small areas, it is generally impossible to determine with any reasonable accuracy the moisture inflow into such storms. While there is no generally accepted procedure for deriving estimates of thunderstorm PMP, the following example from a study /8/ for the semi-arid upper Columbia river basin in north-western United States (Figure 5.34) may serve as a guide. In that region, heavy thunderstorm rainfalls are rarely associated with general-type storms, but occur generally as isolated events.

5.3.6.2 PMP depth-duration relation

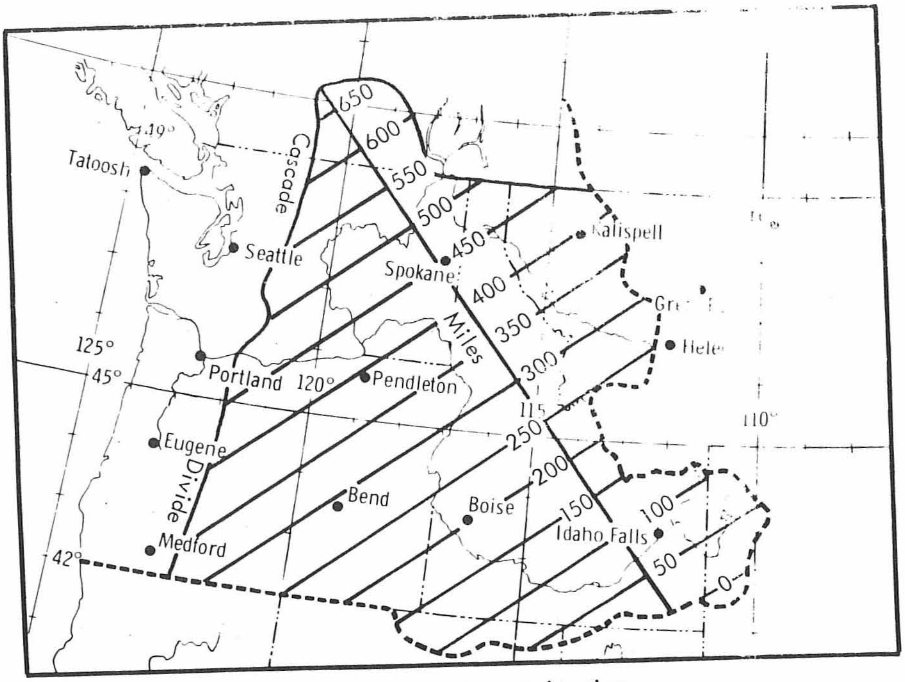
Extreme rainfall amounts for various locations in or near the project region (Figure 5.34) were moisture maximized (section 2.3) to 73°F (22.8°C), the maximum persisting 12-hour 1 000 mb dew point for the extreme south-eastern portion of the project region in August. The maximized values are shown plotted and enveloped in Figure 5.33, which represents thunderstorm PMP values for durations to 6 hours at a point in the extreme south-eastern corner of the project region. Also shown are observed values from storms considered not transposable to the project region. Durations of maximized rainfalls controlling the depth-duration curve did not extend beyond one hour, so ratios of 6- to 1-hour rainfalls in moderate but longer duration thunderstorms were used to extend the curve to six hours. On the basis of experience with dense precipitation networks, an area of 2 km^2 was assigned to the point values.



No.	Station	Date	Observed rain (mm)	Duration (min)	Storm dew point (°C)	Adjusted rain* (mm)
1.	Morgan (nr), Utah	8.16.1958	178	60	19.4	239
2.	Girds Crk., Ore.	7.13.1956	102	30	16.7	168
3.	Simon Ranch, Idaho	7.21.1956	64	20	18.3	94
4.	Birch Crk., Ore.	6.22.1938	64	20	15.0	127
5.	Richland, Ore.	6.15.1954	15	10	15.0	30
6.	Mitchell, Ore.	7.13.1956	89	30	16.7	152
	Following observed rainfalls not transposed - for comparison only:					
7.	Campo, Calif.	8.12.1891	292	80		
8.	Buffalo Gap., Sask., Can.	5.30.1961	267	60		
9.	Chiatovich Flat, Calif.	7.19.1955	210	150		
10.	Fort Mohave, Ariz.	8.28.1898	203	45		

* Adjusted to 22.8°C

Figure 5.33 - Point (2 km^2) thunderstorm PMP for 22.8°C on extreme south-eastern border of upper Columbia river basin



Basin distance from southeast border

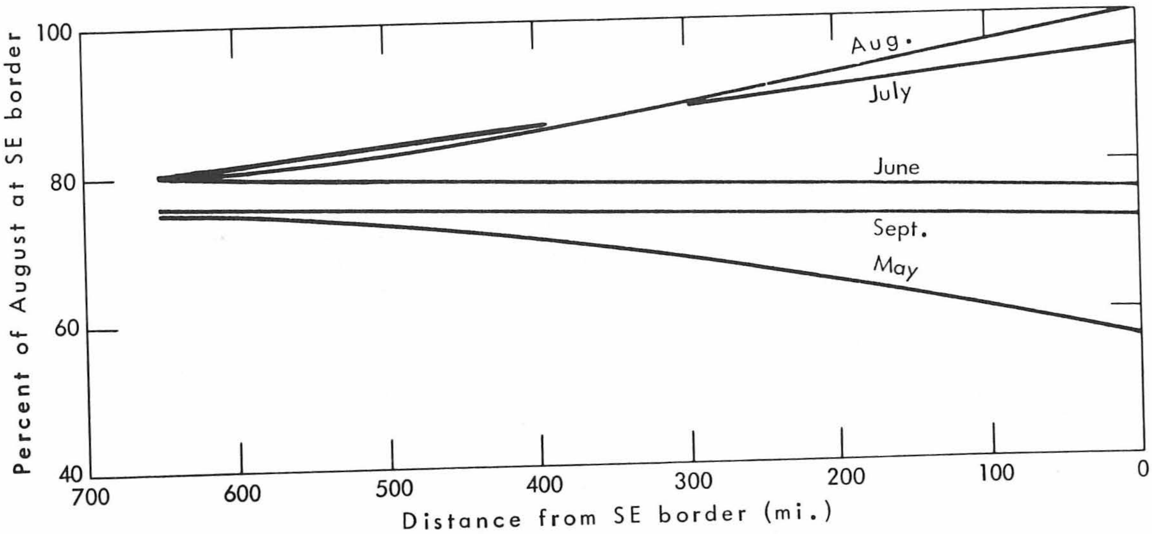


Figure 5.34 - Regional and seasonal variation of thunderstorm PMP

5.3.6.3 Seasonal and regional variations

Thunderstorm rainfalls provide guidance in determining seasonal (within summer months) and regional variations. Amounts for short durations, say 1 and 3 hours, must be obtained from recording-gauge stations, which usually have relatively short records. In the example study, the upper 20 per cent of recording-gauge measurements were used as one guide to the seasonal and regional variations of thunderstorm PMP. Another guide was the variation in maximum moisture with season and region. A composite of the variations indicated by these two types of data resulted in the variations of PMP indicated in Figure 5.34. The parallel lines of the upper chart, which gives distance from the south-eastern border of the project region, are oriented approximately along maximum persisting dew-point lines. The lower diagram, which shows the variation of thunderstorm PMP with month and distance from the south-eastern border, is based on moisture variations indicated by maximum persisting dew points.

5.3.6.4 Elevation adjustment

The observed extreme values of point thunderstorm rainfall occurred at elevations from 300 to 3 000 m. Data were too sparse to indicate any distinct trend with elevation. The much more abundant autographic record extremes, which were considerably smaller, did not provide any definite indication either, although there was a suggestion of a decrease for elevations above 1 500 m. A decrease of 5 per cent for each 300 m above 1 500 m was therefore adopted on the basis of the decrease of moisture in a saturated pseudo-adiabatic atmosphere.

5.3.6.5 Depth-area relation

None of the extreme thunderstorm rainfalls used in developing the PMP depth-duration curve (Figure 5.33) occurred over dense precipitation networks, so the depth-area relation had to be based on other thunderstorms. Analysis of several such storms with adequate data led to the depth-area curves of Figure 5.35.

The areal distribution of thunderstorm rainfall within a basin is often required. One way of showing the areal extent of a storm is to assume circular isohyets and to construct isohyetal profiles of depth against distance from the storm centre, or isohyetal radius (section 2.11.3). Figure 5.36, which is based on the same data as Figure 5.35, shows the adopted isohyetal profile for thunderstorm PMP.

The idealized isohyetal pattern (Figure 5.37) was derived for a model 2-hour thunderstorm. The 2-hour duration was a compromise for each 1-hour PMP increment to simplify procedures for application. The model thunderstorm involved the following assumptions: (a) depth-duration relation as in Figure 5.33; (b) circular isohyets; and (c) storm movement of 4 mile, or 6 km, per hour. The isohyetal pattern, together with Table 5.2, is used to determine average depth of PMP over any portion of a basin. The procedure for evaluating isohyets was described in section 2.11.3.

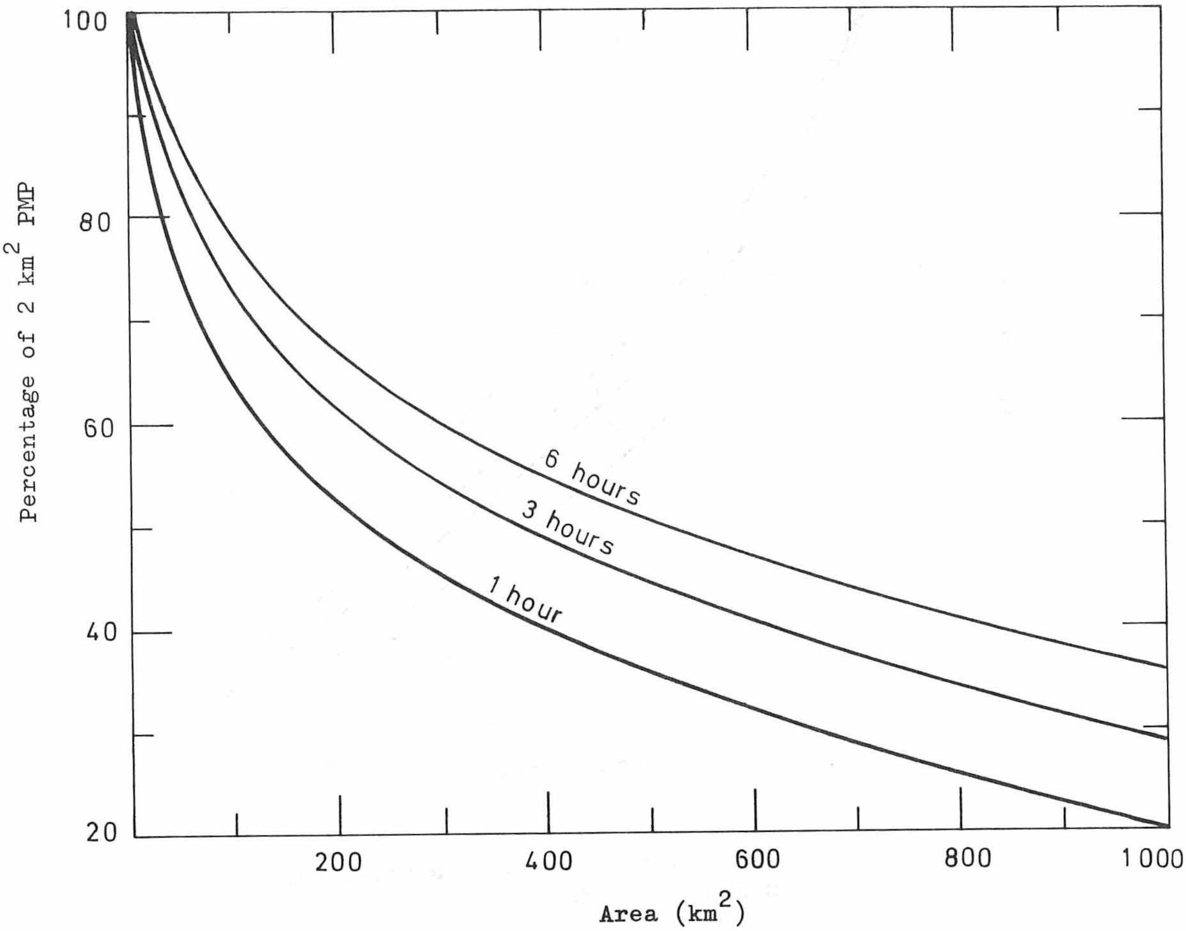


Figure 5.35 - Area-reduction curves for thunderstorm PMP

5.3.6.6 Time distribution

Analysis of time distribution of thunderstorm rainfalls reveals many variations. The following arrangement of hourly increments was recommended: highest increment in second, third or fourth hour, with next highest on either side; third highest adjacent, etc.; and smallest two increments at beginning and end. For example, a possible realistic arrangement would be: 5, 2, 1, 3, 4, 6, where 1 is the greatest increment.

5.3.6.7 Thunderstorm PMP for specific basins

(See cautionary remarks, section 5.4). If the areal distribution of thunderstorm PMP is not required, basin average depths may be obtained as follows.

Step 1. Obtain 1-, 3- and 6-hour values of point, or 2 km^2, PMP from Figure 5.33.

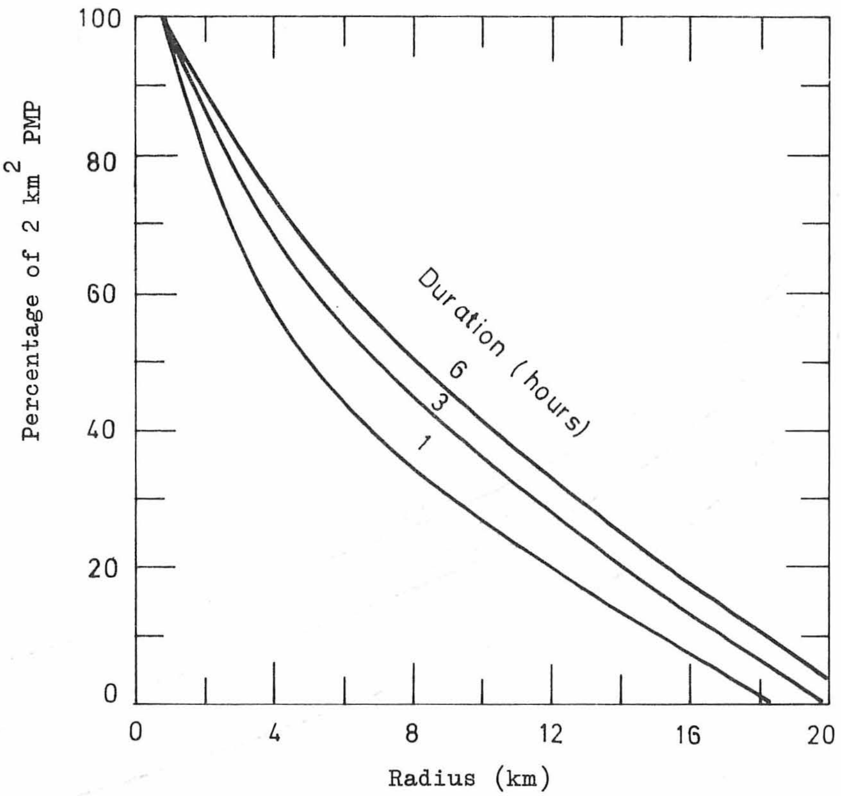


Figure 5.36 - Isohyetal profile for thunderstorm PMP

Step 2. From the upper chart of Figure 5.34, obtain distance of problem basin from south-east border of project region, and use this distance in lower diagram to obtain percentage of August PMP for whatever month(s) required.

Step 3. Multiply PMP values of step 1 by percentage(s) of step 2 to obtain 2 km^2 PMP for location of basin.

Step 4. If lowest elevation in problem basin is above 1 500 m, reduce values obtained in step 3 by 5 per cent for each 300 m above 1 500 m. No adjustment is required if lowest elevation in basin is 1 500 m or lower.

Step 5. Use depth-area-duration curves of Figure 5.35 to obtain percentage adjustments for basin area, and apply to results of step 4 (or step 3 if elevation is not required) in order to determine basin average PMP.

Step 6. Plot basin average PMP values of step 5 against duration, draw smooth enveloping depth-duration curve, and determine hourly increments.

Step 7. Arrange hourly increments as suggested in section 5.3.6.6.

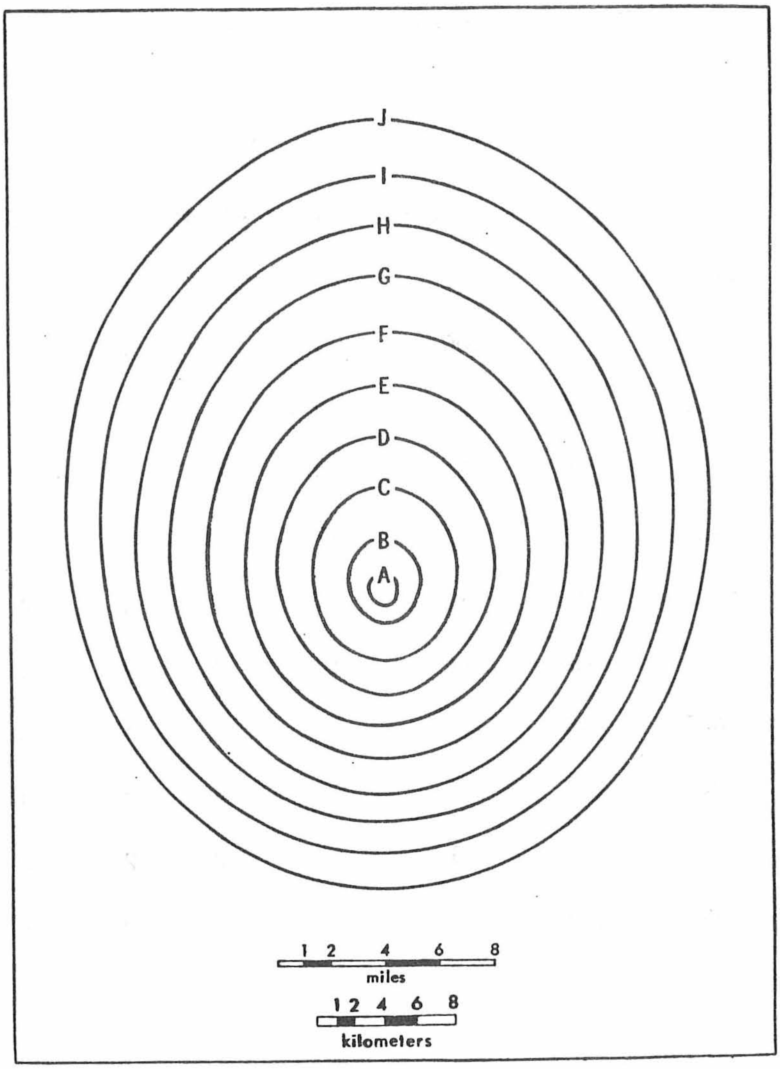


Figure 5.37 - Isohyetal pattern for thunderstorm PMP

If areal distribution of thunderstorm PMP within the basin is required, proceed as follows:

Steps 1-4. Same as above except only 1-hour PMP required.

Step 5. Lay isohyetal pattern (Figure 5.37) over problem basin outline of same scale. Centre and rotate pattern to provide greatest average depth over basin.

Step 6. Obtain labels from Table 5.2 for isohyets up to the minimum size required to enclose basin outline completely.

Table 5.2 - Pattern thunderstorm isohyetal labels (in per cent of 1-hour 2 km^2 PMP)

(1)	(2)		(3)	(4)	(5)	(6)	(7)	(8)
Isohyet	Area enclosed		Hourly increments of PMP in descending order					
	(km^2)	(mile^2)	1st	2nd	3rd	4th	5th	6th
A	2	1	100	19	10	6	5	4
B	16	6	76	19	10	6	5	4
C	65	25	54	19	10	6	5	4
D	153	59	40	17	9	6	5	4
E	246	95	32	14	8	5	4	4
F	433	167	21	10	7	4	3	3
G	635	245	14	7	5	4	3	3
H	847	327	8	4	4	3	3	3
I	1 114	430	1	2	2	2	2	3
J	1 396	539	0	0	0	0	1	3

Step 7. Multiply 1-hour 2 km^2 value of step 4 by isohyetal percentage labels of step 7 to obtain isohyetal values in mm.

Step 8. Determine average depth over basin or portion thereof by planimetering or other procedure.

Step 9. Arrange hourly increments as suggested in section 5.3.6.6.

5.4 Cautionary remarks

Generalized estimates of PMP are representative for individual basins having topographic features similar to the generalized topography used in deriving the estimates. PMP for individual basins with different features may be considerably different from the generalized values, especially in orographic regions. Generalized estimates are generally more representative for the larger basins of the size range considered in this chapter. These larger basins usually have some topographic features similar to those on which the generalized estimates are based. Smaller basins, on the other hand, may have topographic features entirely unlike the general features of the area in which they are located, and generalized estimates therefore tend to be less reliable.

The step-by-step procedures given in this manual for estimating PMP for specific basins serve merely to summarize the methods used in deriving the PMP estimates and the techniques used for applying the results to specific basins. They are not intended to enable the reader to obtain PMP values for specific basins in the regions covered by the examples. For this reason, only those charts and tables required for illustrating the approach used are included. Additional charts and tables would be required for making complete PMP estimates for specific basins.

Other, equally valid approaches besides those represented by the examples have been used for developing generalized estimates. As mentioned earlier, the approach used depends on the geography of the project region and the amount and quality of required data. Basic data requirements for reliable estimates are adequate precipitation networks and dew-point and wind data. A thorough knowledge of meteorological characteristics of storms likely to govern PMP limits is an important requirement. This knowledge is most important where basic data are sparse.

The cautionary remarks of section 2.13 relative to adequacy of storm sample, comparison with record rainfalls, consistency of estimates, seasonal variation, and areal distribution apply to generalized estimates.

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ANNEX 1

TABLES OF PRECIPITABLE WATER IN A SATURATED PSEUDO-ADIABATIC ATMOSPHERE

As stated in Chapter 2, precipitable water is a term used mostly by hydrometeorologists for expressing the total mass of water vapour in a vertical column of the atmosphere. It represents the depth of liquid water that would accumulate at the base of the column if all its water vapour were condensed. The term is a misnomer since no natural process can condense or precipitate all the water vapour in the atmosphere, and substitute terms such as liquid equivalent of water vapour or liquid water equivalent are sometimes used.

The general formula for computing precipitable water, W, in cm, is:

$$W = \overline{q} \Delta p / g \rho \qquad \text{(A.1.1)}$$

where $\overline{q}$ is the mean specific humidity in gm kg^{-1} of a layer of moist air; Δp is the depth of the layer in mb; g is the acceleration of gravity in cm sec^{-2}; and ρ is the density of water, which is equal to 1 gm cm^{-3}.

In much of hydrometeorological work the atmosphere is assumed to contain the same amount of water vapour as saturated air with a saturation pseudo-adiabatic temperature lapse rate. The precipitable water in various layers of the saturated atmosphere can be pre-computed and listed in tables or in nomogram form. Table A.1.1 presents values of precipitable water (mm) between the 1 000 mb surface and various pressure levels up to 200 mb in a saturated pseudo-adiabatic atmosphere as a function of the 1 000 mb dew point. Table A.1.2 lists similar values for layers between the 1 000 mb surface, assumed to be at zero elevation, and various heights up to 17 km.

Table A.1.1 Precipitable water (mm) between 1 000 mb surface and indicated pressure (mb) in a saturated pseudo-adiabatic atmosphere as a function of the 1 000 mb dew point (°C)

mb \ °C	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
990	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1
980	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
970	1	1	1	1	1	2	2	2	2	2	2	2	3	3	3	3
960	1	2	2	2	2	2	2	2	3	3	3	3	3	4	4	4
950	2	2	2	2	2	3	3	3	3	3	4	4	4	4	5	5
940	2	2	2	3	3	3	3	3	4	4	4	5	5	5	6	6
930	2	3	3	3	3	3	4	4	4	5	5	5	6	6	7	7
920	3	3	3	3	4	4	4	5	5	5	6	6	7	7	8	8
910	3	3	3	4	4	4	5	5	5	6	6	7	7	8	8	9
900	3	4	4	4	4	5	5	6	6	6	7	7	8	9	9	10
890	4	4	4	5	5	5	6	6	7	7	8	8	9	9	10	11
880	4	4	4	5	5	6	6	7	7	8	8	9	9	10	11	12
870	4	4	5	5	6	6	7	7	8	8	9	9	10	11	12	13
860	4	5	5	6	6	6	7	7	8	9	9	10	11	12	12	13
850	5	5	5	6	6	7	7	8	9	9	10	11	11	12	13	14
840	5	5	6	6	7	7	8	8	9	10	10	11	12	13	14	15
830	5	5	6	6	7	7	8	9	9	10	11	12	13	14	15	16
820	5	6	6	7	7	8	8	9	10	11	11	12	13	14	15	17
810	5	6	6	7	8	8	9	10	10	11	12	13	14	15	16	17
800	6	6	7	7	8	8	9	10	11	12	12	13	15	16	17	18
790	6	6	7	7	8	9	9	10	11	12	13	14	15	16	17	19
780	6	7	7	8	8	9	10	11	11	12	13	14	16	17	18	19
770	6	7	7	8	9	9	10	11	12	13	14	15	16	17	19	20
760	6	7	7	8	9	10	10	11	12	13	14	15	17	18	19	21
750	6	7	8	8	9	10	11	12	13	14	15	16	17	18	20	21
740	7	7	8	9	9	10	11	12	13	14	15	16	18	19	20	22
730	7	7	8	9	9	10	11	12	13	14	15	17	18	20	21	23
720	7	7	8	9	10	11	11	12	13	15	16	17	18	20	22	23
710	7	8	8	9	10	11	12	13	14	15	16	17	19	20	22	24
700	7	8	8	9	10	11	12	13	14	15	16	18	19	21	23	24
690	7	8	9	9	10	11	12	13	14	15	17	18	20	21	23	25
680	7	8	9	10	10	11	12	13	15	16	17	19	20	22	24	25
670	7	8	9	10	11	11	12	14	15	16	17	19	20	22	24	26
660	8	8	9	10	11	12	13	14	15	16	18	19	21	23	24	26
650	8	8	9	10	11	12	13	14	15	16	18	19	21	23	25	27
640	8	8	9	10	11	12	13	14	15	17	18	20	21	23	25	27
630	8	8	9	10	11	12	13	14	16	17	18	20	22	24	26	28
620	8	9	9	10	11	12	13	14	16	17	19	20	22	24	26	28
610	8	9	9	10	11	12	13	15	16	17	19	20	22	24	26	28
600	8	9	9	10	11	12	13	15	16	17	19	21	23	25	27	29
590	8	9	10	10	11	12	14	15	16	18	19	21	23	25	27	29
580	8	9	10	11	11	13	14	15	16	18	19	21	23	25	27	30
570	8	9	10	11	12	13	14	15	16	18	20	21	23	25	27	30
560	8	9	10	11	12	13	14	15	17	18	20	21	23	26	28	30
550	8	9	10	11	12	13	14	15	17	18	20	22	24	26	28	30
540	8	9	10	11	12	13	14	15	17	18	20	22	24	26	28	31
530	8	9	10	11	12	13	14	15	17	18	20	22	24	26	28	31
520	8	9	10	11	12	13	14	16	17	19	20	22	24	26	29	31
510	8	9	10	11	12	13	14	16	17	19	20	22	24	26	29	31
500	8	9	10	11	12	13	14	16	17	19	20	22	24	27	29	32
490	8	9	10	11	12	13	14	16	17	19	21	22	25	27	29	32
480	8	9	10	11	12	13	14	16	17	19	21	23	25	27	29	32
470	8	9	10	11	12	13	14	16	17	19	21	23	25	27	29	32
460	8	9	10	11	12	13	14	16	17	19	21	23	25	27	30	32
450	8	9	10	11	12	13	14	16	17	19	21	23	25	27	30	32
440	8	9	10	11	12	13	15	16	17	19	21	23	25	27	30	33
430	8	9	10	11	12	13	15	16	17	19	21	23	25	27	30	33
420	8	9	10	11	12	13	15	16	18	19	21	23	25	27	30	33
410	8	9	10	11	12	13	15	16	18	19	21	23	25	27	30	33
400	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33
390	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33
380	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33
370	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33
360	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33
350	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33
340	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33
330	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33
320	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33
310	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33
300	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33
290	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33
280	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33
270	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33
260	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33
250	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33
240	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33
230	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33
220	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33
210	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33
200	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33

Table A. 1.1 (continued)

mb	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30 °C
990	1	1	1	1	1	1	2	2	2	2	2	2	2	2	3
980	2	2	2	3	3	3	3	3	4	4	4	4	5	5	5
970	3	4	4	4	4	5	5	5	5	6	6	7	7	7	8
960	4	5	5	5	6	6	6	7	7	8	8	9	9	10	11
950	6	6	6	7	7	8	8	9	9	10	10	11	12	12	13
940	7	7	7	8	9	9	10	10	11	12	12	13	14	15	16
930	8	8	9	9	10	11	11	12	13	14	14	15	16	17	18
920	9	9	10	10	11	12	13	14	14	15	16	17	19	20	21
910	10	10	11	12	13	13	14	15	16	17	18	20	21	22	23
900	11	11	12	13	14	15	16	17	18	19	20	22	23	24	24
890	12	12	13	14	15	16	17	18	20	21	22	24	25	27	28
880	12	13	14	15	16	17	19	20	21	23	24	26	27	29	31
870	13	14	15	16	18	19	20	21	23	24	26	28	29	31	33
860	14	15	16	18	19	20	21	23	24	26	28	30	32	34	36
850	15	16	18	19	20	21	23	24	26	28	30	32	34	36	38
840	16	17	19	20	21	23	24	26	28	30	32	34	36	38	40
830	17	18	19	21	22	24	26	27	29	31	33	35	38	40	43
820	18	19	20	22	24	25	27	29	31	33	35	37	40	42	45
810	19	20	21	23	25	26	28	30	32	34	37	39	42	44	47
800	19	21	22	24	26	28	29	32	34	36	38	41	44	46	49
790	20	22	23	25	27	29	31	33	35	38	40	43	46	49	52
780	21	23	24	25	28	30	32	34	37	39	42	45	48	51	54
770	22	23	25	27	29	31	33	35	38	41	43	46	49	53	56
760	22	24	26	28	30	32	34	37	39	42	45	48	51	55	58
750	23	25	27	29	31	33	35	38	41	44	47	50	53	57	60
740	24	26	25	30	32	34	37	39	42	45	48	51	55	59	62
730	24	26	28	30	33	35	38	40	43	46	50	53	57	60	64
720	25	27	29	31	34	36	39	42	45	48	51	55	58	62	65
710	26	28	30	32	35	37	40	43	46	49	53	56	60	64	68
700	26	28	31	33	35	38	41	44	47	50	54	58	62	66	70
690	27	29	31	34	36	39	42	45	48	52	55	59	63	68	72
680	27	30	32	34	37	40	43	46	49	53	57	61	65	69	74
670	28	30	33	35	38	41	44	47	51	54	58	62	67	71	76
660	29	31	33	35	39	42	45	48	52	55	60	64	68	73	78
650	29	31	34	37	39	42	46	49	53	57	61	65	70	75	80
640	29	32	35	37	40	43	46	50	54	58	62	67	71	76	81
630	30	32	35	38	41	44	47	51	55	59	63	68	73	78	83
620	30	33	36	38	42	45	48	52	56	60	65	69	74	79	85
610	31	33	36	39	42	45	49	53	57	61	66	71	76	81	87
600	31	34	37	40	43	46	50	54	58	62	67	72	77	82	[illegible]
590	32	34	37	40	43	47	51	55	59	63	68	73	78	84	90
580	32	35	38	41	44	48	51	55	60	64	69	74	80	85	91
570	32	35	38	41	45	48	52	56	61	65	70	75	81	87	93
560	33	36	39	42	45	49	53	57	61	66	71	77	82	88	94
550	33	36	39	42	46	49	53	58	62	67	72	78	83	90	96
540	33	36	39	43	46	50	54	59	63	68	73	79	85	91	97
530	34	37	40	43	47	50	55	59	64	69	74	80	86	92	99
520	34	37	40	43	47	51	55	60	64	70	75	81	87	93	100
510	34	37	40	44	48	51	56	60	65	70	76	82	88	95	102
500	34	37	41	44	48	52	56	61	66	71	77	83	89	96	103
490	35	38	41	45	48	52	57	61	66	72	78	84	90	97	104
480	35	38	41	45	49	53	57	62	67	73	78	85	91	98	105
470	35	38	42	45	49	53	58	62	68	73	79	85	92	99	106
460	35	38	42	45	49	54	58	63	68	74	80	86	93	100	108
450	35	39	42	46	50	54	58	63	69	74	81	87	94	101	109
440	35	39	42	46	50	54	59	64	69	75	81	88	95	102	110
430	36	39	42	46	50	55	59	64	70	76	82	88	96	103	111
420	36	39	43	46	50	55	60	65	70	76	82	89	96	104	112
410	36	39	43	47	51	55	60	65	71	77	83	90	97	105	113
400	36	39	43	47	51	55	60	65	71	77	84	90	98	105	114
390	36	39	43	47	51	56	60	66	71	77	84	91	98	106	115
380	36	39	43	47	51	56	61	66	72	78	85	92	99	107	115
370	36	40	43	47	51	56	61	66	72	78	85	92	100	108	116
360	36	40	43	47	51	56	61	66	72	79	85	93	100	109	117
350	36	40	43	47	52	56	61	67	73	79	86	93	101	109	118
340	36	40	43	47	52	56	61	67	73	79	85	93	101	109	118
330	36	40	43	47	52	56	61	67	73	79	86	94	102	110	119
320	36	40	44	48	52	57	62	67	73	80	87	94	102	111	120
310	36	40	44	48	52	57	62	67	73	80	87	94	102	111	120
300	36	40	44	48	52	57	62	67	74	80	87	95	103	111	121
290	36	40	44	48	52	57	62	68	74	80	87	95	103	112	121
280	36	40	44	48	52	57	62	68	74	80	88	95	103	112	121
270	36	40	44	48	52	57	62	68	74	81	88	95	104	112	122
260	36	40	44	48	52	57	62	68	74	81	88	96	104	113	122
250	36	40	44	48	52	57	62	68	74	81	88	96	104	113	122
240	36	40	44	48	52	57	62	68	74	81	88	96	104	113	123
230	36	40	44	48	52	57	62	68	74	81	88	96	104	113	123
220	36	40	44	48	52	57	62	68	74	81	88	96	104	113	123
210	36	40	44	48	52	57	62	68	74	81	88	96	105	114	123
200	36	40	44	48	52	57	62	68	74	81	88	96	105	114	123

Table A.1.2 Precipitable water (mm) between 1 000 mb surface and indicated height (m) above that surface in a saturated pseudo-adiabatic atmosphere as a function of the 1 000 mb dew point (°C)

Height (m)	1 000 mb Temperature (°C) 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
200	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2
400	2	2	2	2	2	3	3	3	3	3	4	4	4	4	5	5
600	3	3	3	3	3	4	4	4	5	5	5	6	6	6	7	7
800	3	3	4	4	4	5	5	5	6	6	7	7	8	8	9	9
1 000	4	4	4	5	5	6	6	6	7	7	8	9	9	10	10	11
1 200	4	5	5	6	6	7	7	8	8	9	9	10	11	11	12	13
1 400	5	5	6	6	7	7	8	8	9	10	10	11	12	13	14	15
1 600	5	6	6	7	7	8	9	9	10	11	11	12	13	14	15	16
1 800	6	6	7	7	8	9	9	10	11	12	12	13	14	15	17	18
2 000	6	7	7	8	9	9	10	11	11	12	13	14	16	17	18	19
2 200	7	7	8	8	9	10	10	11	12	13	14	15	16	18	19	20
2 400	7	8	8	9	9	10	11	12	13	14	15	16	17	19	20	22
2 600	7	8	8	9	10	11	11	12	13	14	16	17	18	20	21	23
2 800	7	8	9	9	10	11	12	13	14	15	16	18	19	21	22	24
3 000	8	8	9	10	10	11	12	13	14	15	17	18	20	21	23	25
3 200	8	8	9	10	11	12	13	14	15	16	17	19	20	22	24	26
3 400	8	8	9	10	11	12	13	14	15	16	18	19	21	23	24	26
3 600	8	9	9	10	11	12	13	14	15	17	18	20	22	23	25	27
3 800	8	9	10	10	11	12	13	14	16	17	19	20	22	24	26	28
4 000	8	9	10	11	11	12	14	15	16	17	19	21	22	24	26	28
4 200	8	9	10	11	12	13	14	15	16	18	19	21	23	25	27	29
4 400	8	9	10	11	12	13	14	15	16	18	20	21	23	25	27	29
4 600	8	9	10	11	12	13	14	15	17	18	20	22	24	25	28	30
4 800	8	9	10	11	12	13	14	15	17	18	20	22	24	26	28	30
5 000	8	9	10	11	12	13	14	16	17	19	20	22	24	26	28	31
5 200	8	9	10	11	12	13	14	16	17	19	20	22	24	26	29	31
5 400	8	9	10	11	12	13	14	16	17	19	20	22	24	26	29	31
5 600	8	9	10	11	12	13	14	16	17	19	21	22	24	27	29	32
5 800	8	9	10	11	12	13	14	16	17	19	21	22	25	27	29	32
6 000	8	9	10	11	12	13	15	16	17	19	21	23	25	27	30	32
6 200	8	9	10	11	12	13	15	16	17	19	21	23	25	27	30	32
6 400	8	9	10	11	12	13	15	16	18	19	21	23	25	27	30	33
6 600	8	9	10	11	12	13	15	16	18	19	21	23	25	27	30	33
6 800	8	9	10	11	12	13	15	16	18	19	21	23	25	27	30	33
7 000	8	9	10	11	12	14	15	16	18	19	21	23	25	28	30	33
7 200	8	9	10	11	12	14	15	16	18	19	21	23	25	28	30	33
7 400	8	9	10	11	12	14	15	16	18	19	21	23	25	28	30	33
7 600	8	9	10	11	12	14	15	16	18	19	21	23	25	28	30	33
7 800	8	9	10	11	12	14	15	16	18	19	21	23	25	28	30	33
8 000	8	9	10	11	12	14	15	16	18	19	21	23	26	28	30	33
8 200	8	9	10	11	12	14	15	16	18	19	21	23	26	28	30	33
8 400	8	9	10	11	12	14	15	16	18	19	21	23	26	28	30	33
8 600	8	9	10	11	12	14	15	16	18	19	21	23	26	28	30	33
8 800	8	9	10	11	12	14	15	16	18	19	21	23	26	28	30	33
9 000	8	9	10	11	12	14	15	16	18	19	21	23	26	28	31	33
9 200	8	9	10	11	12	14	15	16	18	19	21	23	26	28	31	33
9 400						14	15	16	18	19	21	23	26	28	31	33
9 600						14	15	16	18	19	21	23	26	28	31	33
9 800						14	15	16	18	19	21	23	26	28	31	33
10 000						14	15	16	18	19	21	23	26	28	31	33
11 000											21	23	26	28	31	33
12 000																33

Table A.1.2 (continued)

Height (m)	1 000 mb Temperature (°C) 16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
200	3	3	3	3	3	4	4	4	4	4	5	5	5	6	6
400	5	5	6	6	6	7	7	8	8	9	9	10	10	11	12
600	7	8	8	9	10	10	11	11	12	13	14	15	15	16	17
800	10	10	11	12	13	13	14	15	16	17	18	19	20	21	22
1 000	12	13	13	14	15	16	17	18	20	21	22	23	25	26	28
1 200	14	15	16	17	18	19	20	21	23	24	26	27	29	31	32
1 400	16	17	18	19	20	22	23	24	26	28	29	31	33	35	37
1 600	17	19	20	21	23	24	25	27	29	31	33	35	37	39	41
1 800	19	20	22	23	25	26	28	30	32	34	36	39	41	43	46
2 000	21	22	24	25	27	29	31	33	35	37	39	42	44	47	50
2 200	22	24	25	27	29	31	33	35	37	40	42	45	48	51	54
2 400	23	25	27	29	31	33	35	37	40	43	45	48	51	54	57
2 600	24	26	28	30	32	35	37	40	42	45	48	51	55	58	61
2 800	26	27	30	32	34	36	39	42	45	48	51	54	58	61	65
3 000	27	29	31	33	35	38	41	44	47	50	53	57	61	64	68
3 200	28	30	32	34	37	40	42	45	49	52	56	59	63	67	71
3 400	29	31	33	36	38	41	44	47	51	54	58	62	66	70	74
3 600	29	32	34	37	39	42	45	49	52	56	60	64	68	73	77
3 800	30	32	35	38	41	44	47	50	54	58	62	66	70	75	80
4 000	31	33	36	39	42	45	48	52	56	60	64	68	73	78	83
4 200	31	34	37	40	43	46	49	53	57	61	66	70	75	80	85
4 400	32	34	37	40	44	47	51	54	58	63	67	72	77	82	87
4 600	32	35	38	41	44	48	52	56	60	64	69	74	79	84	90
4 800	33	36	39	42	45	49	53	57	61	65	70	75	81	86	92
5 000	33	36	39	42	46	50	54	58	62	67	72	77	82	88	94
5 200	34	37	40	43	47	50	54	59	63	68	73	78	84	90	96
5 400	34	37	40	44	47	51	55	60	64	69	74	80	86	92	98
5 600	35	38	41	44	48	52	56	60	65	70	76	81	87	93	100
5 800	35	38	41	45	48	52	57	61	66	71	77	82	88	95	101
6 000	35	38	42	45	49	53	57	62	67	72	78	84	90	96	103
6 200	35	38	42	45	49	54	58	63	68	73	79	85	91	98	104
6 400	35	39	42	46	50	54	58	63	68	74	80	86	92	99	106
6 600	36	39	42	46	50	54	59	64	69	74	80	87	93	100	107
6 800	36	39	42	46	50	55	60	65	70	75	81	87	94	101	108
7 000	36	39	43	46	51	55	60	65	70	76	82	88	95	102	110
7 200	36	39	43	47	51	55	60	65	71	76	82	89	96	103	111
7 400	36	39	43	47	51	56	61	66	71	77	83	90	97	104	112
7 600	36	39	43	47	51	56	61	66	72	77	83	90	98	105	113
7 800	36	39	43	47	51	56	61	66	72	78	84	91	98	106	114
8 000	36	40	43	47	52	56	61	67	72	78	85	92	99	107	115
8 200	36	40	43	47	52	57	62	67	73	78	85	92	100	108	115
8 400	36	40	43	47	52	57	62	67	73	79	85	92	100	108	116
8 600	36	40	43	47	52	57	62	68	73	79	86	93	101	109	117
8 800	36	40	43	47	52	57	62	68	73	79	86	93	101	109	118
9 000	36	40	43	47	52	57	62	68	74	80	86	94	102	110	118
9 200	36	40	43	48	52	57	62	68	74	80	87	94	102	110	119
9 400	36	40	44	48	52	57	62	68	74	80	87	94	102	110	119
9 600	36	40	44	48	52	57	63	68	74	80	87	94	102	111	120
9 800	36	40	44	48	52	57	63	68	74	80	87	95	103	111	120
10 000	37	40	44	48	52	57	63	68	74	80	87	95	103	112	121
11 000	37	40	44	48	52	57	63	68	74	81	88	96	104	113	122
12 000	37	40	44	48	52	57	63	63	74	81	88	96	105	114	123
13 000					52	57	63	68	74	81	88	97	105	114	124
14 000					52	57	63	68	74	81	88	97	105	115	124
15 000										81	88	97	106	115	124
16 000										81	88	97	106	115	124
17 000											89	97	106	115	124

A N N E X 2

GREATEST KNOWN RAINFALLS

World-wide record and near-record rainfalls are listed in Tables A.2.1 and A.2.2 respectively. The values of Table A.2.1 are shown plotted against duration in Figure A.2.1, which also gives the equation of the straight envelope, with R being the rainfall in inches, and D, the duration in hours.

The extreme rainfall values of Tables A.2.1 and A.2.2 may be used in judging the general level of PMP for some locations. Such values are associated with a small number of storm types and geographic locations, and their applicability is limited. The record values of Table A.2.1 for 9 hours to 8 days are from two different tropical storms on the Island of La Reunion in the Indian Ocean. There, typhoons, or cyclones as they are called in that part of the world, collide with steep mountains reaching up to over 3 000 metres under circumstances so favourable for rain that the resulting deluge is not readily transposable to other regions lacking equally steep and high mountains so close to the sea. The near-record rainfall values listed for China in Table A.2.2 suggest that its PMP may be of the same order of magnitude as that for La Reunion. For locations of less rugged topography, lower values of PMP might be expected, and there is then justification for excluding the values listed for La Reunion and China in Tables A.2.1 and A.2.2 as guides for estimating PMP.

Since the values listed in Tables A.2.1 and A.2.2 for durations from 4 hours to 8 days are mostly from tropical storms, they should not be used as indicators of PMP magnitude in regions not frequented by such storms. Obviously, small-area PMP in cold climates or over basins well protected by orographic barriers and located far enough from their crests so as not to be affected by spillover will fall considerably below the values listed in these two tables.

The point values of Tables A.2.1 and A.2.2 may be reduced to areas up to 1 000 km^2 by means of Figure 4.6. This reduction for size of area is far from a refined procedure since such area-reduction curves vary both regionally and with storm type. These curves are generally too unreliable to permit the point values of these two tables from being used as guides to PMP estimates for large basins. World-record and near-record rainfall values on a volumetric basis are unavailable. Table A.2.3 gives maximum depth-area-duration data obtained from some 700 analyzed storms in the United States. The large majority of these listed data are from tropical storms, and caution should be used in developing ratios from this table for use in other regions.

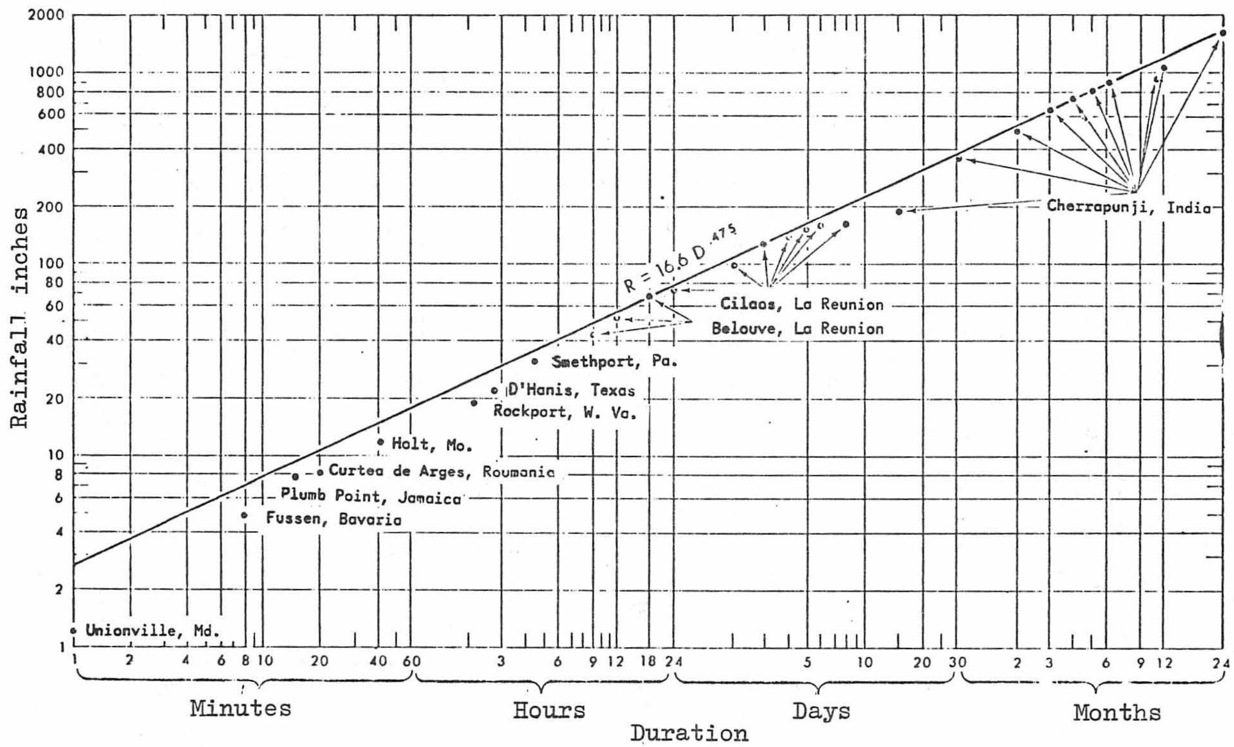

Figure A.2.1 – World's greatest observed point rainfalls

Table A.2.1 World's greatest observed point rainfalls

Duration	Depth (in)	Depth (mm)	Location	Date
1 min	1.50	38	Barot Guadeloupe	26 Nov. 1970
8 min	4.96	126	Fussen, Bavaria	25 May 1920
15 min	7.80	198	Plumb Point, Jamaica	12 May 1916
20 min	8.10	206	Curtea-de-Arges, Roumania	7 July 1889
42 min	12.00	305	Holt, Mo.	22 June 1947
2 h 10 min	19.00	483	Rockport, W. Va.	18 July 1889
2 h 45 min	22.00	559	D'Hanis, Tex. (17 mi. NNW.)	31 May 1935
4 h 30 min	30.8+	782	Smethport, Pa.	18 July, 1942
9 h	42.79	1 087	Belouve, La Reunion	28 Feb. 1964
12 h	52.76	1 340	Belouve, La Reunion	28-29 Feb. 1964
18 h 30 min	66.49	1 689	Belouve, La Reunion	28-29 Feb. 1964
24 h	73.62	1 870	Cilaos, La Reunion	15-16 Mar. 1952
2 d	98.42	2 500	Cilaos, La Reunion	15-17 Mar. 1952
3 d	127.56	3 240	Cilaos, La Reunion	15-18 Mar. 1952
4 d	137.95	3 504	Cilaos, La Reunion	14-18 Mar. 1952
5 d	151.73	3 854	Cilaos, La Reunion	13-18 Mar. 1952
6 d	159.65	4 055	Cilaos, La Reunion	13-19 Mar. 1952
7 d	161.81	4 110	Cilaos, La Reunion	12-19 Mar. 1952
8 d	162.59	4 130	Cilaos, La Reunion	11-19 Mar. 1952
15 d	188.88	4 798	Cherrapunji, India	24 June - 8 July, 1931
31 d	366.14	9 300	Cherrapunji, India	July 1861
2 mo	502.63	12 767	Cherrapunji, India	June-July 1861
3 mo	644.44	16 369	Cherrapunji, India	May-July 1861
4 mo	737.70	18 738	Cherrapunji, India	Apr.-July 1861
5 mo	803.62	20 412	Cherrapunji, India	Apr.-Aug 1861
6 mo	884.03	22 454	Cherrapunji, India	Apr.-Sept 1861
11 mo	905.12	22 990	Cherrapunji, India	Jan.-Nov. 1861
1 yr	1 041.78	26 461	Cherrapunji, India	Aug. 1860-July 1861
2 yr	1 605.05	40 768	Cherrapunji, India	1860-1861

Table A.2.2 Near-record rainfalls

Duration	Depth (in)	Depth (mm)	Location	Date
1 min	0.65	17	Opid's Camp, Calif.	5 Apr. 1926
5 min	2.48	63	Porto Bello, Panama	29 Nov. 1911
14 min	3.95	100	Galveston, Tex.	4 June 1871
40 min	9.25	235	Guinea, Va.	24 Aug. 1906
1 h	10.00	254	Catskill, N.Y.	26 July 1819
1 h 20 min	11.50	292	Campo, Calif.	21 Aug. 1891
3 h	16.00	406	Concord, Pa.	5 Aug. 1843
4 h	23.00	584	Basseterre, St. Kitts, W. Indies	12 Jan. 1880
12 h	30.72	780	Baguio, Philippines	17 Oct. 1967
15 h	34.50	876	Smethport, Pa.	17-18 July 1942
18 h	36.40	925	Thrall, Tex.	9 Sept. 1921
21 h	41.7	1 059	Kadena Air Force Base, Okinawa	8 Sept. 1956
24 h	65.83	1 672	Hsin-liao, China	17 Oct. 1967
24 h	49.13	1 248	Paishih, China	10-11 Sept. 1963
24 h	47.86	1 216	Baguio, Philippines	17-18 Oct. 1967
24 h	40.80	1 036	Cherrapunji, India	14 June 1876
24 h	40.10	1 019	Jowai, India	11 Sept. 1897
39 h	62.39	1 585	Baguio, Philippines	14-16 July 1911
2 d	88.94	2 259	Hsin-liao, China	17-18 Oct. 1967
2 d	82.11	2 086	Bowden Pen, Jamaica	22-23 Jan. 1960
2 d	63.64	1 616	Cherrapunji, India	14-15 June 1876
2 d 15 h	79.12	2 010	Baguio, Philippines	14-17 July 1911
3 d	108.21	2 749	Hsin-liao, China	17-19 Oct. 1967
3 d	99.52	2 528	Bowden Pen, Jamaica	22-24 Jan. 1960
3 d	80.52	2 045	Cherrapunji, India	25-27 June 1931
3 d 15 h	87.01	2 210	Baguio, Philippines	14-18 July 1911
4 d	109.79	2 789	Bowden Pen, Jamaica	22-25 Jan. 1960
4 d	101.84	2 587	Cherrapunji, India	12-15 June 1876
5 d	114.50	2 908	Silver Hill Plantation, Jamaica	5-9 Nov. 1909
5 d	114.14	2 899	Cherrapunji, India	12-16 June 1876
6 d	122.50	3 112	Silver Hill Plantation, Jamaica	5-10 Nov. 1909
6 d	119.37	3 032	Cherrapunji, India	11-16 June 1876
7 d	131.15	3 331	Cherrapunji, India	24-30 June 1931
7 d	129.00	3 277	Silver Hill Plantation, Jamaica	4-10 Nov. 1909
8 d	135.05	3 430	Cherrapunji, India	24 June-1 July 1931
8 d	135.00	3 429	Silver Hill Plantation, Jamaica	4-11 Nov. 1909

Table A.2.3 Maximum observed depth-area-duration data for the United States (Average rainfall in inches and (millimeters))

Area	Duration (hours) 6	12	18	24	36	48	72
10 mile^2 26 km^2	24.7a (627)	29.8b (757)	36.3c (922)	38.7c (983)	41.8c (1062)	43.1c (1095)	45.2c (1148)
100 mile^2 259 km^2	19.6b (498)	26.3c (668)	32.5c (826)	35.2c (894)	37.9c (963)	38.9c (988)	40.6c (1031)
200 mile^2 518 km^2	17.9b (455)	25.6c (650)	31.4c (798)	34.2c (869)	36.7c (932)	37.7c (958)	39.2c (996)
500 mile^2 1 295 km^2	15.4b (391)	24.6c (625)	29.7c (754)	32.7c (831)	35.0c (889)	36.0c (914)	37.3c (947)
1 000 mile^2 2 590 km^2	13.4b (340)	22.6c (574)	27.4c (696)	30.2c (767)	32.9c (836)	33.7c (856)	34.9c (886)
2 000 mile^2 5 180 km^2	11.2b (284)	17.7c (450)	22.5c (572)	24.8c (630)	27.3c (693)	28.4c (721)	29.7c (754)
5 000 mile^2 12 950 km^2	8.1bj (206)	11.1b (282)	14.1b (358)	15.5c (394)	18.7d (475)	20.7d (526)	24.4d (620)
10 000 mile^2 25 900 km^2	5.7j (145)	7.9k (201)	10.1e (257)	12.1e (307)	15.1d (384)	17.4d (442)	21.3d (541)
20 000 mile^2 51 800 km^2	4.0j (102)	6.0k (152)	7.9e (201)	9.6e (244)	11.6d (295)	13.8d (351)	17.6d (447)
50 000 mile^2 129 500 km^2	2.5eh (64)	4.2g (107)	5.3e (135)	6.3e (160)	7.9e (201)	8.9e (226)	11.5f (292)
100 000 mile^2 259 000 km^2	1.7h (43)	2.5ih (64)	3.5e (89)	4.3e (109)	5.6e (142)	6.6f (168)	8.9f (226)

Storm	Date	Location of centre	
a	17-18 July 1942	Smethport, Pa.	
b	8-10 Sept 1921	Thrall, Tex.	
c	3-7 Sept 1950	Yankeetown, Fla.	Hurricane
d	27 June-1 July 1899	Hearne, Tex.	
e	13-15 Mar 1929	Elba, Ala.	
f	5-10 July 1916	Bonifay, Fla.	Hurricane
g	15-18 Apr 1900	Eutaw, Ala.	
h	22-26 May 1908	Chattanooga, Okla.	
i	19-22 Nov 1934	Millry, Ala.	
j	27 June-4 July 1936	Bebe, Tex.	
k	12-16 Apr 1927	Jefferson Parish, La.	

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