• CANADIAN SOCIETY FOR CIVIL ENGINEERING
6th CANADIAN HYDROTECHNICAL CONFERENCE
• JUNE 2 and 3, 1983
OTTAWA, ONTARIO

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6e CONFÉRENCE CANADIENNE D'HYDROTECHNIQUE
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CLIMATIC CHANGE AND THE PLANNING OF WATER RESOURCE SYSTEMS

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SYNOPSIS

Storage reservoirs represent the core of most large water resource systems serving flood protection, low-flow augmentation and water supply, and hydro-power generation. Reliable estimation of reservoir effectiveness in controlling the streamflow is thus an important component in the planning and design of water resource system. This estimation is complicated by the uncertainty in streamflow during the working life of the reservoir, i.e. during a future 50-100 years. Further uncertainties arise in the case of a climate change. In this paper, results of a recent study on the impact of climate change on streamflow are analyzed from the point of view of their statistical significance vis-à-vis the uncertainties in estimates of reservoir effectiveness.

KEYWORDS

Water resource systems; climate change impact; water resource planning; streamflow control; reservoir regulation; hydrological modelling.

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RESUME

Les réservoirs représentent le coeur de la plupart des réseaux importants de ressources en eau servant à la protection contre les crues, à l'augmentation d'un débit peu élevé, à l'approvisionnement en eau et à la production d'hydro-électricité. Il est donc important de posséder une estimation fiable de l'efficacité d'un réservoir afin d'être en mesure de planifier et de concevoir un réseau de ressources en eau. Cette estimation est difficile à établir vu l'impossibilité de prédire avec certitude le débit qui sera enregistré au cours de la vie utile d'un réservoir, c'est-à-dire pour les 50 à 100 prochaines années. Un changement climatique soulève également d'autres incertitudes. Dans le présent document, on analyse les conclusions d'une étude effectuée récemment au sujet des effets d'un changement climatique sur le débit du point de vue de leur signification statistique face aux incertitudes qui se posent dans l'évaluation de l'efficacité d'un réservoir.

INTRODUCTION

Climatologists claim that a man-induced climate change is a very likely possibility and can occur within the next few decades. So far, interest has been focussed on one particular cuase of this change, namely on an increase of CO_2 concentration in the atmosphere due to the world-wide intensive consumption of fossil fuels. The present consensus of experts seems to be that a doubling of atmospheric CO_2 will lead to an increase of temperature by about 2°C and will be accompanied by substantial changes in precipitation, evaporation, and runoff. While the quantitative predictions are subject to errors due to the lack of adequate knowledge of the physical mechanisms involved, the fact remains that a climate change could have a substantial effect on water resurces and those sectors of the economy which depend on them.

From the water management point of view, three questions arise, 1) what is the range of magnitude of the foreseeable changes in the available water resources, 2) how will they affect the present water management capabilities, and 3) what can be done about the problem in the planning of water resource development measures?

It is fairly obvious that everything hinges on the answer to the first question. Unless we know how much the available water resources are likely to change, we cannot estimate the effect on water management and can take no remedial action in the planning process.

The fundamental question of "how much?" was recently addressed by a Panel on water and climate of the U.S. National Academy of Sciences (1977) and the answer was in general pessimistic: based on current knowledge,the magnitude of the change cannot be estimated and hence very little can be done about it at the present time.

Němec and Schaake (1982) are more optimistic and claim that hydrologic modelling can provide reasonable estimates of the quantitative changes in water resources and thus facilitate a consideration of climate change in the design and operation of water resource systems. As an example, they demonstrate the use of the Sacramento hydrological model for a simulation of streamflow sequences corresponding to changed conditions of the climate in two U.S. river basins, and the use of these sequences for an assessment of future performance characteristics of storage reservoirs.

This paper reports on the results of an analysis of the Němec-Schaake study from the point of view of its value to the planning of surface water resources and storage reservoirs (Klemeš, 1982a).

GENERAL CONCEPT

The general concept adopted by Němec and Schaake is to take a river basin for which historic records of precipitation, temperature, and streamflow are available, fit the Sacramento model (or, in general, any adequate conceptual hydrological model) to the data, then change the precipitation and potential evapotranspiration (computed from temperature) according to a postulated climate scenario and use the model to simulate the corresponding streamflow series. In the last step they use the simulated streamflow series as input into a storage reservoir, evaluate its performance criteria and compare them with those obtained on the basis of the historic streamflow record.

CLIMATOLOGY

Recognizing the fact that a consensus of experts cannot be equated with an unequivocal scientific evidence, Němec and Schaake consider 12 different climate scenarios characterized by all combinations of the following changes of precipitation P and potential evapotranspiration E:

P = 25%, 10%, -10% and -25%;
E = 12%, 4%, and -4%.

Thus, rather than taking sides in the climate change controversy, they propose to investigate a wide range of possibilities which comfortably accommodates most of the competing hypotheses. This broadening of the scope is, in effect, tantamount to a negative answer to questions NO. 1 nd 3 posed above and limits the area of inquiry to conditional answers to question No. 2, i.e. to a sensitivity analysis of the response of water resource development to climate changes as the authors explicitly state. One weakness of this approach is that no differentiation is possible between scenarios which are physically plausible but practically unlikely and those which may be physically implausible. An additional weakness arises from the fact that the above listed changes were imposed on the historic records uniformly, i.e. each historic daily precipitation and evapotranspiration value was changed by the percentage corresponding to the given scenario, for instance by 25% and 4%, respectively. Such uniformity is unlikely. The prevailing opinion is that the changes will be different in different seasons of the year while the pattern will vary with latitude (Manabe and Stouffer, 1980).

HYDROLOGY

From the hydrological point of view, the main problem is whether and to what extent a conceptual model is "climatically transferable", i.e whether it can be expected to perform satisfactorily under conditions different from those for which it has been calibrated. It is well known that conceptual hydrological models of the present generation are not geographically

transferrable since their parameters do not reflect specific physical conditions but represent merely numerical coefficients applied to the input variables with the sole purpose of minimizing the differences between the simulated and recorded streamflows. In general, the same can be expected in connection with climatic transferability. Moreover, it has been amply demonstrated (WMO, 1975) that conceptual models, including the Sacramento model, don't perform well in arid conditions even if they have been calibrated for them. The principal difficulty is that, unlike the geographic transferability, the climatic transferability of hydrologic models cannot be rigorously tested. Only comparatively weak testing is possible with the aid of differential split sample tests (Klemeš, 1982b), but even this has not been carried out in the present case. It thus can be concluded that the simulated streamflow sequences can be regarded only as responses of the model to different sets of forcing functions, and that their correspondence to the specific climate scenarios is at best approximate. The whole exercise represents only a first step in the assessment of the sensitivity of climate-change impact via the modelling route. Its main value is in that it highlights the weak points in the art of modelling and indicates the direction of climate and hydrology research necessary for a better understanding of the problem.

STATISTICAL SIGNIFICANCE OF WATER RESOURCES SENSITIVITY TO CLIMATE CHANGE

In the following assessment of statistical significance of the sensitivity of surface water resources (represented by streamflow series from the Němec-Schaake study), the climatological and hydrological reservations cited above have not been considered and the simulated streamflow series are taken at their face value. In other words, the analysis addresses the problem on the unlikely assumption that the simulated streamflow series are truly representative of the respective climate change scenarios for the two basins under consideration (Table 1).

Table 1. Characteristics of River Basins under Study

	Leaf River (Collins, Mississippi)	Pease River (Vernon, Texas)
Basin area	1949 km^2	9034 km^2
Mean annual precipitation	1314 mm	540 mm
Mean annual runoff	409 mm	11 mm
Length of record used in streamflow modelling	18 years	11 years

A good overall characteristic of the potential of surface water resources is the statistical distribution of annual runoff

volume (or mean annual flow). In the given cases, this distribution is approximately lognormal so that all information about it is contained in its mean and standard deviation. This simplifies the analysis in that it can be limited to investigating the impact of precipitation and evapotranspiration changes on only these two parameters. In this representation, the response of the water resource potential of the two basins to the 12 climate scenarios is shown in Figs. 1 and 2 by the 12 points in the mean-standard deviation plane. In general, it is obvious that the major differences arise form the change in precipitation while the impact of evapotranspiration (i.e. of temperature from which the latter has been estimated) is relatively minor.

The problem of statistical significance of these differences arises from the fact that both the mean and the standard deviation have been computed from finite, and relatively very short, samples and are contaminated by large sampling errors. Thus each point shown in Figs. 1 and 2 must be regarded as a sample point from a bivariate distribution of mean and standard deviation. The true parameters of this distribution are not known. All one can do is to estimate a "confidence region" (at a given significance level) where a point defined by them must be in order for them to be compatible with the sample parameters represented by the point plotted. In this study a 90% significance level was chosen and the corresponding confidence region was obtained via the Monte Carlo technique. The confidence regions were constructed only for the base (historic) flow series and for the simulated cases corresponding to evapotranspiration change of 4%. Figs. 1 and 2 show that, given the lengths of the series (Table 1) from which the parameters have been computed,the differences corresponding to the evapotranspiration changes are not significant for any single precipitation change. The extent of overlap of two regions indicates the extent of statistical "insignificance" of the differences between the corresponding samples and, by implication, between the corresponding climate scenarios. This is so because of the possibility that both samples could originate from the same population if the parameters of the latter define a point inside the overlap.

While the present analysis has stopped here, the problem itself does not. In the planning context, it is not enough to identify the region within which the population parameters are likely to be found since within the planning horizon only one sample from the unknown population will be effective. Thus, from the planning point of view, one would have to specify confidence regions linking the compatibility of the historic sample with a future sample of a length equal to the length of the planning horizon (the elipses in Figs. 1 and 2 correspond, so to speak, to an infinite planning horizon); work on this problem is in progress.

SENSITIVITY OF SURFACE WATER DEVELOPMENT POTENTIAL

The surface water development potential is conveniently characterized by a reliability with which a given rate of flow

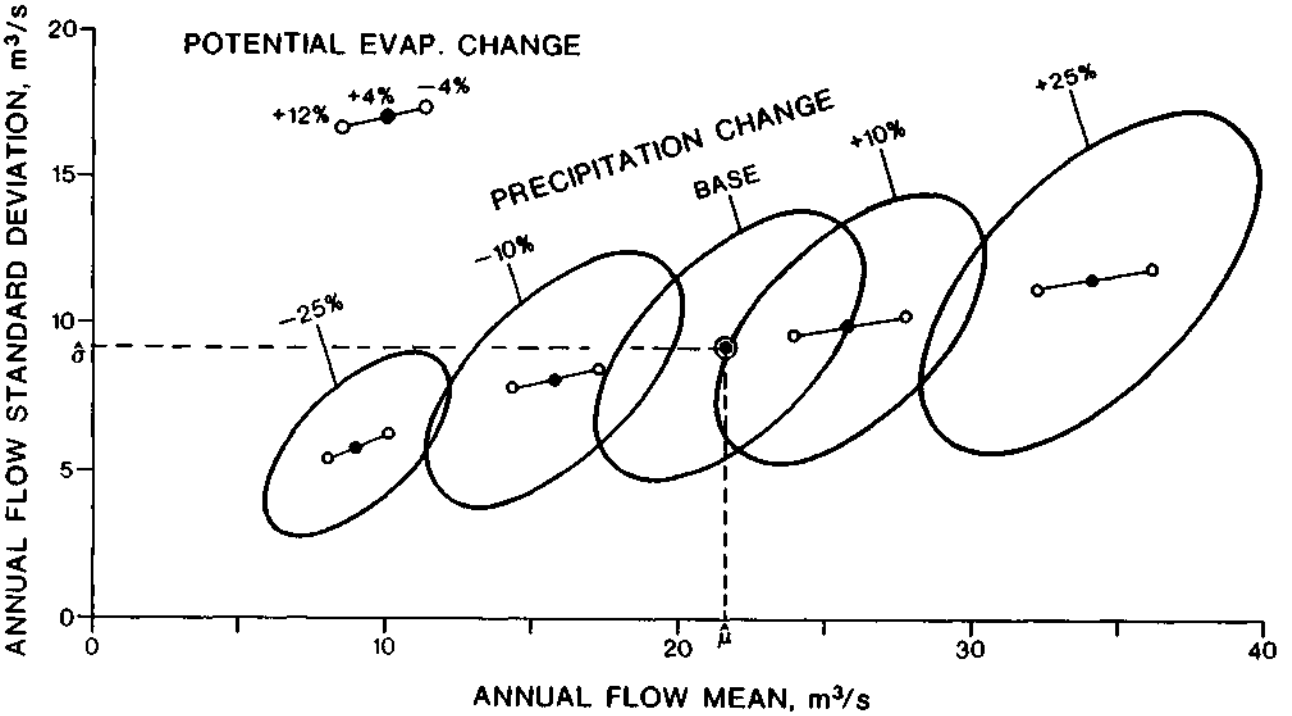

Fig. 1 Leaf River. 90% confidence regions for joint distributions of means and standard deviations for sample size N = 18 from five lognormal distributions centered on the historic series (Base) and those corresponding to potential evaporation change of +4%.

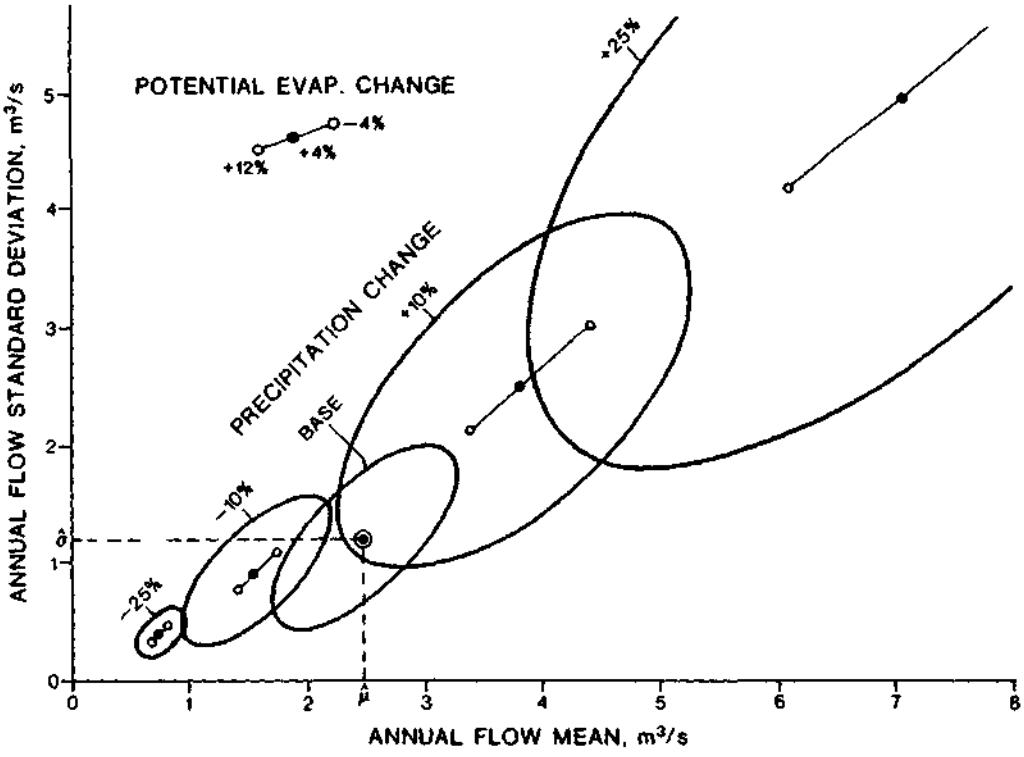

Fig. 2 Peace River. 90% confidence regions for joint distributions of means and standard deviations for sample size N = 11 from five lognormal distributions centered on the historic series (Base) and those corresponding to potential evaporation change of +4%.

(target draft) can be assured. Under virgin conditions, this reliability is equal to the natural exceedance frequency (cumulative duration) of the target draft. This reliability can be increased by a storage reservoir designed to augment flows lower than the target draft by water stored during periods when the natural rate of flow is higher than the target draft. The relationship between the target draft, its reliability, and the reservoir storage capacity is often called the "reservoir regime function" (also storage-yield function, etc.) and depends on the stochastic properties of the streamflow process. Hence the differences between regime functions based on streamflow series corresponding to different climate scenarios are indicative of the sensitivity of surface water development potential to climate change. Regime functions have been constructed for both basins, in each case for the historic flow series and for all the twelve climate scenarios. As an example, three regime functions for the Leaf River are shown in Figs. 3, 4 and 5. For a given level of water resource development (i.e. for a specified combination of target release and reservoir storage capacity), the sensitivity to climate change is characterized by the difference between the corresponding reliability obtained from the regime function for the given scenario and the reliability obtained from the regime function based on the historic flow record.

It can be seen that the effect of climate change can, to a degree, be compensated for by a change in reservoir storage capacity. Thus, for instance, if water demand in the basin calls for a target draft of 8 m^3/s delivered with a 90% reliability, it would now be necessary to build a reservoir with an active storage capacity of about 60 mill m^3. Should however the climate become drier (scenario P = -25%, E = 4%) the reservoir would have to be increased to a storage capacity of 370 mill m^3 in order for the 90% reliability to be maintained. However, the important point which was not mentioned by Nemec and Schaake is that the possibility to compensate for dryness by increased storage is not absolute. For example, a 95% reliability of a target release equal to 15 m^3/s (present storage required is 300 mill m^3) cannot be restored under the dry scenario considered previously by whatever increase of storage capacity - its maximum theoretical reliability attainable for such a scenario would be less than 40% - a value which under the present climate is attained without any reservoir.

STATISTICAL SIGNIFICANCE OF RELIABILITY DIFFERENCES

The reigme functions shown in Figs. 3, 4 and 5 were constructed on the basis of short streamflow series and are subject to sampling errors as any other characteristics or parameters derived from them. To obtain an idea about the statistical significance of the reliability differences deduced from the sample-based regime functions, a detailed analysis was carried out for four levels of development for the Leaf River, in particular for target drafts equal to 19.3 m^3/s, 15.0 m^3/s, 10.8 m^3/s and 6.5 m^3/s. In all four cases, the present reliabilty was considered the same and equal to 95% so that the storage capacities

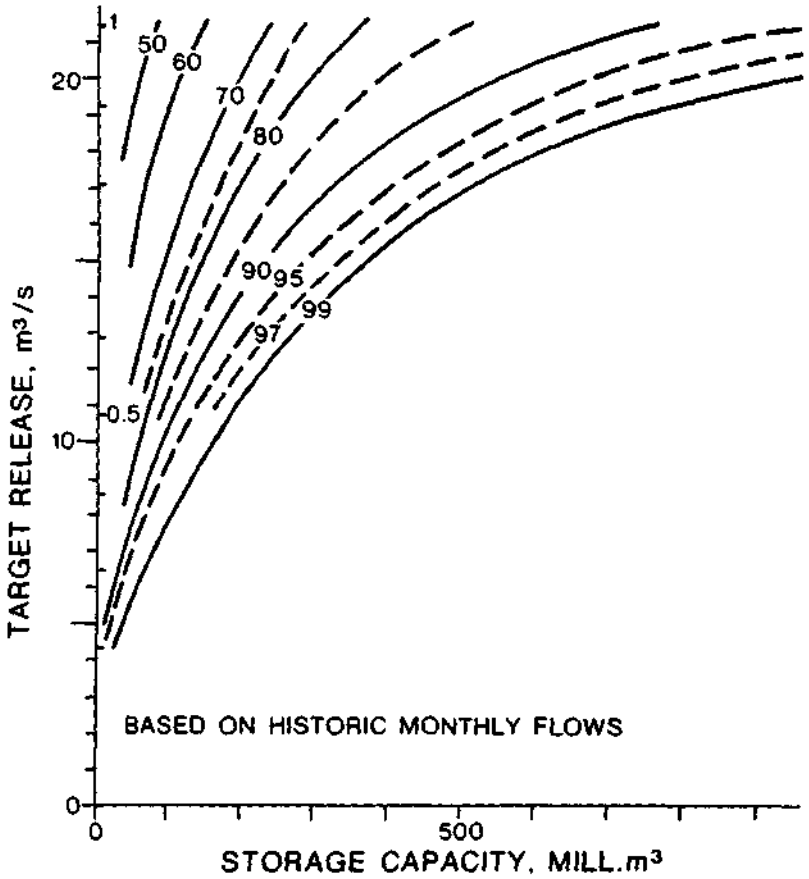

Fig. 3 Leaf River. Time-based reliability (in %) of flow regulation for stationary conditions of operation over an 18-year historic period.

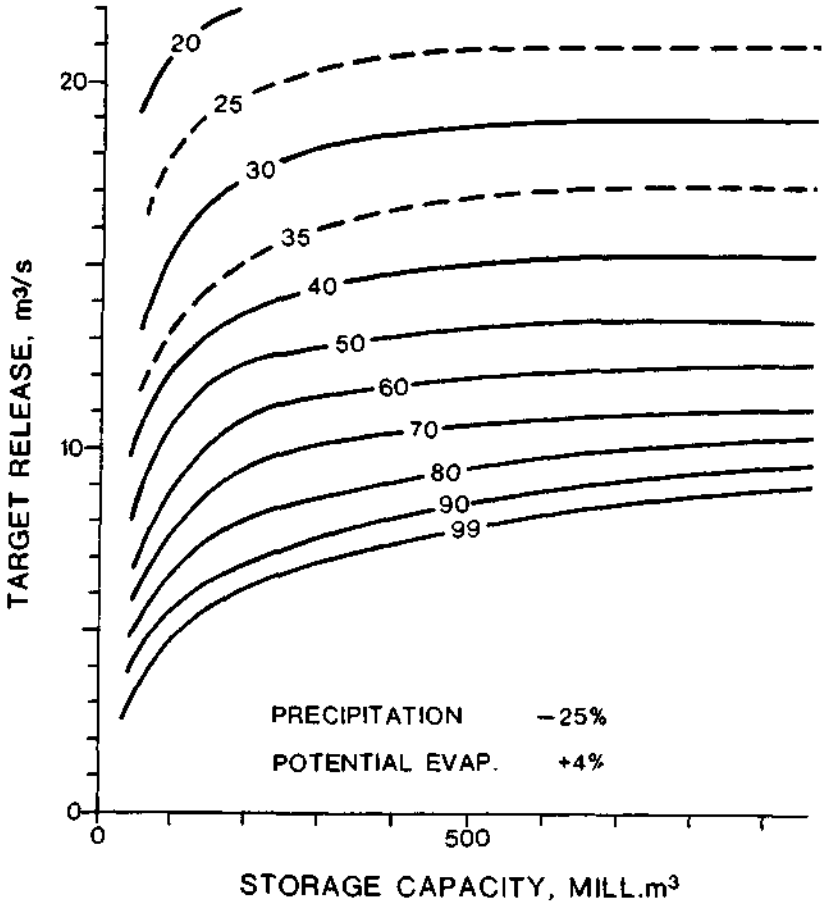

Fig. 4 Leaf River. Time-based reliability (in %) of flow regulation for stationary conditions over an 18-year period corresponding to the indicated changes in precipitation and potential evaporation.

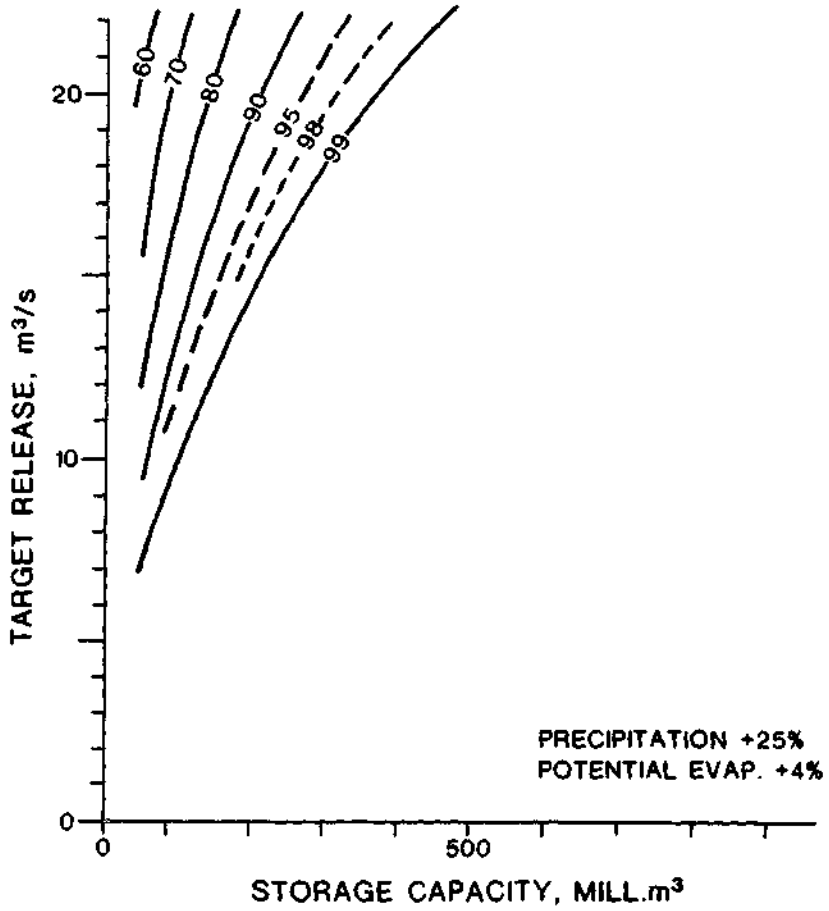

Fig. 5 Leaf River. Time-based reliability (in %) of flow regulation for stationary conditions over an 18-year period corresponding to the indicated changes in precipitation and potential evaporation.

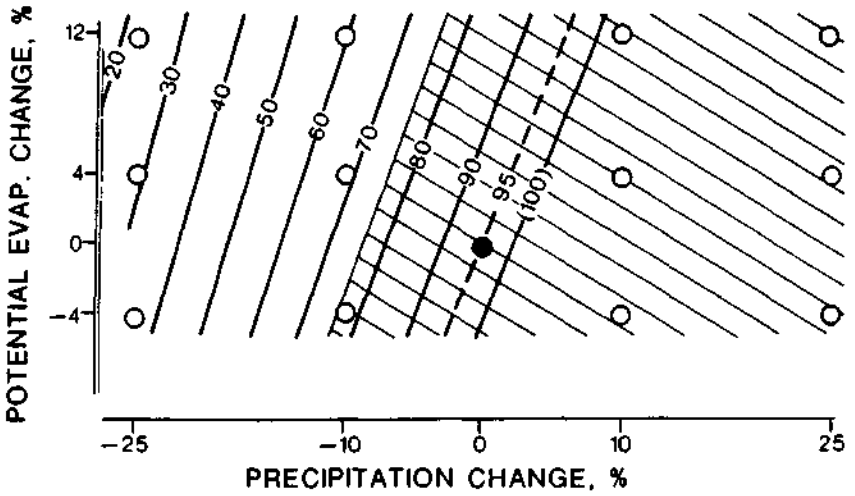

Fig. 6 Leaf River, development level: target release = 19.3 m^3/s, storage = 600 mill m^3. Time reliability (in %) as a function of changes in precipitation and potential evaporation. Shaded areas represent 90% confidence bands on the 95% reliability applicable to present conditions.

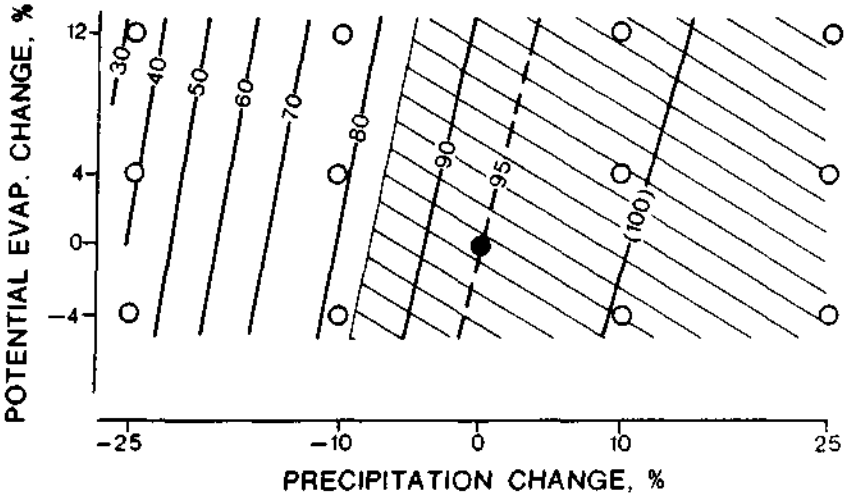

Fig. 7 Leaf River, development level: target release = 15.0 m^3/s, storage = 280 mill m^3. Time reliability (in %) as a function of changes in precipitation and potential evaporation. Shaded areas represent 90% confidence bands on the 95% reliability applicable to present conditions.

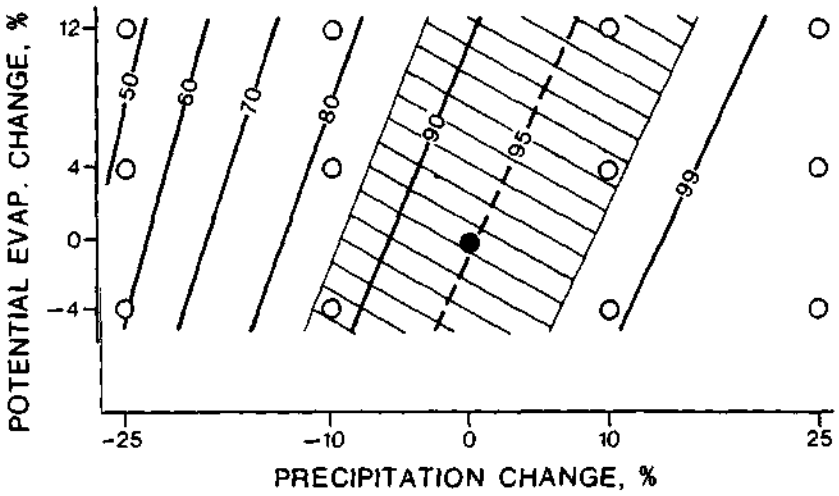

Fig. 8 Leaf River, development level: target release = 10.8 m^3/s, storage = 125 mill m^3. Time reliability (in %) as a function of changes in precipitation and potential evaporation. Shaded areas represent 90% confidence bands on the 95% reliability applicable to present conditions.

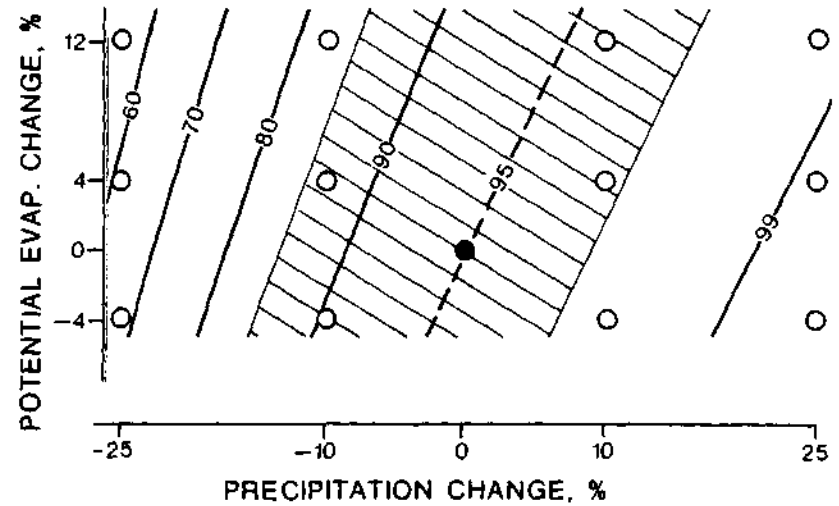

Fig. 9 Leaf River, development level: target release = 6.5 m^3/s, storage = 40 mill m^3. Time reliability (in %) as a function of changes in precipitation and potential evaporation. Shaded areas represent 90% confidence bands on the 95% reliability applicable to present conditions.

required were 600, 280, 125 and 40 mill m^3, respectively. For each storage capacity and the corresponding target draft the reliabilities for all climate scenarios were obtained and mapped onto the plane of precipitation and potential evapotranspiration changes (Figs. 6, 7, 8, 9). Thus, for example, Fig. 9 shows that a storage of 40 mill m^3 which is enough to assure a draft of 6.5 m^3/s with a 95% reliability under present climate, would assure the same draft with only a 90% reliability in the scenario {P = -10%, E = -4%} and with only a 60% reliability in the sceanrio {P = -25%, E = 4%}.

However, these reliability differences must be evaluated in terms of their statistical significance since each value (i.e. the value for each scenario) was derived from a short flow series and it is conceivable that a different series from the same scenario would yield a different reliability value for the same target draft and storage. In this study, the statistical significance was evaluated in detail only for the reliability value of 95% corresponding to the present climate. For this purpose a stochastic model was fitted to the historic series of monthly flows and 300 series of the same length as the historic series were generated for 300 random pairs of population means and standard deviations of annual flows drawn from their bivariate distribution. For each series the reliability of the given development level was found and a histogram from the 300 reliability values constructed. A 90% confidence interval was then determined from the historgram by truncating its tails at 5% and 95% levels. The corresponding reliability range was then entered onto the map for the corresponding development level. The shaded strip thus represents a 90% confidence region for the reliability value of 95%. The circles which lie inside the shaded area identify the scenarios for which the difference in reliability indicated by the map is not statistically significant at a 90% level. It should be noted that the type of the stochastic model employed made it possible to construct the reliability confidence regions only for the planning horizon equal to the length of the historic record which in Figs. 6, 7, 8 and 9 is 18 years.

CONCLUSIONS

Apart from the climatological and hydrological uncertainties the quantification of which was not feasible in the present case, the sampling uncertainties arising from the shortness of the employed historic record impose by themselves considerable limitations on the usefulness of modelling of the hydrological impact of climate change. It transpires that, based on historic records of about 20 years (which are quite typical in water resource planning and design), the sampling error in the data combined with the sampling uncertainty in the conditions during the future operation period are of the same order of magnitude as the changes ascribed to a moderate change in the climate. Thus, even if the direction of the climate change were certain (which it is not), there would be very little the water planner could do in addition to what he has to do anyway – i.e. to take into account a possibility

that the future can be hydrologically considerably different from the past. The practical consequence for the planner is to be cautious and refrain from pushing the development of the present resources to the limit. In other words, the time-honoured engineering practice of keeping a safety margin as a hedge against uncertainty is even more commendable from the perspective of climate change than it is without it.

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