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USING HYDROLOGICAL MODELING IN FORESTRY

P.Y. Bernier
Laurentian Forestry Centre
Ste.-Foy, Quebec

ABSTRACT

Forest managers must look at water from two perspectives: as a resource for downstream use and as an essential element for forest survival and growth. Hydrological modeling can help the forest manager protect the water resource for downstream use. Hydrological concepts, whether or not in models, can also be put to many applications in forestry. Determination of inherent site productivity and of "plantation windows," as well as the management of tree water demand and of soil water supply through modifications in block size, shape, and orientation are examples of direct applications of hydrology to forestry. Most models cannot be used for management purposes because of their complexity and their demanding input needs. A procedure for determining the effect of changes in forest cover on water yield called WRENSS has been derived from water balance models and is an excellent example of how models can be simplified and made usable on a day-to-day basis by forest managers.

INTRODUCTION

There are two ways to view the relation between forestry and water. The first is to view water as a resource in its own right, usually intended for downstream use. The second is to view water as an element essential for forest growth. Traditionally, the "water as a resource" view has been prevalent, as reflected by the fact that this presentation was put in the "other resource sectors" portion of this symposium. In this view, the relation is one of parallel management, in that the actions of forestry can influence the quantity, quality, and timing of streamflow. Thus, the management of trees and water are inextricably tied together through the action of man on the environment, and those ties often place the management of these two resources in conflict with one another. Models are important management tools in this context because they assess the impact of forestry operations on the water resource.

Trees are water consumers, however, and the level of equilibrium between water demand and water availability is often critical for the survival and growth of trees. In this view, the relation is one of dependency in that forest management can influence, and is influenced by, the tree's water demand and the site's water availability. The study of the water available to trees and the water consumed by trees thus should not be classified off-hand as an "other resource sector" because many hydrological concepts can and should be used to improve forest management practices. We will see later that modeling efforts currently under way attempt to improve forestry practices using hydrological knowledge.

MODELS AND HYDROLOGICAL MODELING

I will not dwell on what a model is, since by this time you will have heard many definitions from previous speakers. I would just like to add that a model is not necessarily an impressive assemblage of computer code. One-line equations that present an empirical view of reality are also models in their own right. And, often, complex computer models are just fancy representations of such one-line models!

The term "hydrological model" can be loosely defined as a model centered around one or more of the phases of the hydrological cycle. Thus, snowmelt models, evapotranspiration (ET) or microclimatic models, and groundwater models are all hydrological models. This definition is rather broad; because of the importance of water in the environment, many models incorporate some method of accounting for water without being formally recognized as hydrological models.

Most hydrological models are process-based. Processes represent physical actions taking place at a specific location over a specific amount of time. Snowmelt, for example, is a well-modeled process (e.g., Leaf and Brink 1973a; Anderson 1976; Price and Dunne 1976; Smith et al. 1976; Obled and Rosse 1977; Weismann 1977; Cooley 1986). Infiltration, or the movement of water in the saturated or unsaturated portions of the soil, is also well modeled. Expansion of a one-time-step simple-process model can go in many directions. The model can be expanded in time to simulate the process over a longer period or expanded in space to simulate the spatial variability of the process over a hill slope or a basin or both. Process models can be linked or layered to represent more complete pathways of water movement, say from snowmelt, to soil percolation to streamflow, or to represent a more complete picture of yearly cycles in water pathways, with, for example, snowmelt in the spring and ET in the summer. The separation between evapotranspiration models, snowmelt models, water yield models, or other hydrological models is often a matter of degree of representation of the different processes.

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Traditional Applications: In-stream Effects

As I mentioned in the introduction, there are two ways of looking at water: as a resource for downstream use and as an essential component for forest survival and growth. First, in the realm of downstream use, the influence of forestry can be felt on the quantity, timing, and quality of the water in the streams. In Canada, except for a few municipal catchments, there is currently no river basin where forests are managed specifically for the enhancement or the protection of the water resource. Forested lands are prime suppliers of surface waters, however. For example, Laycock (1965) computed that for a moderately dry year, 95% of the flow in the South Saskatchewan River was generated in its forested headwaters covering only 20% of the basin area. It is therefore understandable that the protection of the water resource should be at least an implicit constraint in the management of the timber resource. Models exist, or are being developed, to help the forest managers in this task.

1. Water Yield

Forestry operations can dramatically influence water yields of a basin. In experiments conducted in Alberta (Swanson and Hillman 1977; Swanson et al. 1986) and in Colorado (Bates and Henry 1928; Troendle and Leaf 1981), the annual water yield increase per hectare clear-cut ranged from 250 to 1800 m^3. The smaller increase was obtained from one 80-ha clear-cut, while the highest increase was obtained in Colorado by using 1-ha cut blocks. Partial clear-cuts with 10-20 ha blocks in Alberta have produced 800 m^3 of extra water per hectare annually. The yield increase is the result of reductions in losses through transpiration and losses through evaporation from intercepted snow following the removal of the forest cover. The effect of cut size on yield increase is due to wind and shading effects. Small cuts trap snow and reduce its evaporation. Large cuts expose the snow to wind-driven transport and evaporation. The effect of the cut on water yield declines gradually over the next 10-30 years as the forest grows back.

Models that compute annual water yields are called water balance models, meaning that they are simply models that keep track of inputs and outputs of water into a system. In their simplest form, water balance models include a procedure for computing evapotranspiration (ET), one for computing snowmelt (at least for our snowy regions), and a soil-defined storage unit that "overflows" into a "water yield" bucket. One widely used water balance model developed by Leaf and Brink in 1973 is now the base for the WRENSS procedure, which will be discussed later in this presentation.

2. Streamflow Regime (Timing and Magnitude)

Forestry operations also affect the distribution of streamflow over the year. Low flows are increased through increased soil reserves. Snowmelt runoff is advanced or retarded depending on the exposition of the hill slope. Peak flows are increased or unchanged depending on the source of water (rain or melt) and on the magnitude of the event. A good example of these effects can be found in Swanson and Hillman (1977). Forestry effects on spring and summer flood peaks and on summer low flows are often at the heart of disputes between forestry companies and local residents. In British Columbia, for example, there is substantial concern about the effect of forestry on the flood flows that accompany rain-on-snow events. The modeling of forestry effects on streamflow regime is probably the best way to avoid or solve these conflicts.

Models that compute streamflow usually start off with a water balance component that computes hourly, daily, or weekly amounts of "nonevapotranspired" water that is available for streamflow on the basin. Streamflow models take these amounts and transform them through more or less complex routing procedures into actual streamflow at a particular point in a stream, usually a gauging site. So, in addition to climate- and vegetation-related inputs, streamflow models require information on topography, physical properties of soils, and even channel morphology. In many instances all of these extra variables are rolled into a few (or many) adjustable parameters whose values are obtained by calibration. One such streamflow model currently under study at the Northern Forestry Centre is the HSPF model, a model developed at Stanford University in California.

3. *Water Quality: Migration of Sediments*

The impact of forestry on erosion and sedimentation is as varied as the terrain covered by forestry operations. How much erosion occurs over a clearcut area depends on many factors, including topography, soil type, precipitation regime, the type of forestry operation, and its location with respect to stream channels. Erosion is detrimental to both water quality and site quality, and the estimation of erosion potential of forestry activities has been part of the objectives of numerous research programs in the prairie provinces (Swanson et al. 1986; van der Vinne and Andres 1989) and elsewhere (Ursic 1986; Burt et al. 1984; Rice et al. 1979). In general, it has been found that the worst erosion problems are usually associated with poor road construction practices. Models have been developed to help predict the effect of forestry on the rate of erosion from logged areas.

Unlike water balance models, erosion-sedimentation models usually proceed on a storm-by-storm basis, because the erosion caused by a storm is unaffected by previous rainfall. Forest hydrologists have generally modified Wischmeier's Universal Soil Loss Equation (Wischmeier and Smith 1960), an agricultural erosion model, for forestry conditions. One such adaptation is that by Burns and Hewlett (1983). Another, far more complex one, is offered by Warrington et al. (1980).

4. *Water Quality: Migration of Chemicals*

The ongoing controversy surrounding the use of herbicides in forestry clearly outlines the need for methods to predict the environmental fate of chemicals once they are sprayed or applied over a basin. Unfortunately, chemical routing models are probably the most complex of all hydrological models. Such models must include a water balance model to simulate the quantity and timing of water entry into the soil and a complete soil water routing function as in the best of streamflow models. Chemical routing models must also incorporate a component that keeps track of chemical reactions between the compound of interest and the soil, including degradation into secondary components and retention on exchange sites. This is an area where modeling is still struggling to represent what is actually happening in the field.

New Applications: Hydrology and Tree Growth

As I said before, water is not only a resource that has to be managed in parallel to the timber resource. Water is also a key factor in the growth and survival of trees, as are light and nutrients. In fact, in many parts of western North America, water availability with respect to water demand is probably the most limiting factor for tree survival and growth. There are many aspects of operational forestry that can benefit a great deal from the application of hydrological concepts, whether through modeling or not. I will illustrate below three such applications.

1. *Evaluating Site Productivity*

The productivity of a site is often determined from measurements made on the stand already existing on the site; however, the growth pattern of the stand has already been influenced not only by the inherent productivity of the site but by many other factors like initial density of the stand, fire, insect and disease outbreaks; and competition from other plant species. As mentioned before, in many parts of western North America, including the Rocky Mountain foothills, water is the most limiting factor for tree growth. By linking a water balance model to a tree growth model, one can therefore estimate the inherent potential of the site for growing timber.

Applications for such a model go far beyond that of regular site index classification. Users can compute the growth potential of currently nonforested sites, compare sites stocked with different species, or even estimate the effect of a summer drought or a snowless winter on annual wood increment. Such models already exist. A good example of this type of model is DAYTRANS (Running 1984a, b), which computes daily water requirements of the tree (Douglas-fir), the soil water supply, and in a feedback loop, the effect of the water supply on photosynthesis and transpiration.

2. *Determining Plantation Windows*

Another application of hydrological modeling in forestry is the determination of planting windows. Using a water balance model for cutover sites, and linking such a model to seedling water requirements, one can compute whether or not a seedling will survive if planted. With such a model, and using many years of data, planners can determine which period of summer is on average more conducive to successful planting on different sites. Real-time computations can also be carried out to determine if conditions are right for planting. An example of such a modeling effort is given by Childs et al. (1987).

3. *Planning Cuts to Maximize Water Available to the Trees*

This last application is one for which there exists no formal model. The survival and establishment of seedlings and the growth of trees is largely controlled by how the plant's evaporative needs are matched by the availability of water. By altering the size, shape, and orientation of clear-cuts according to their aspect, exposure, and the height of surrounding trees, we can modify both water demand and water supply through increased snow-trapping efficiency, protection from wind, and shading. Other factors such as roughness of cuts, choice of species, and competition also influence water availability and demand. Through models we can study the interactions of all these parameters and specify site-specific management practices that will insure the best use of available energy and water for tree growth.

WRENSS: AN OPERATIONAL EXAMPLE

Hydrological models are usually not made for management purposes but rather for research purposes, or at best, for consultive management. Typical water-balance models require site-specific meteorological data supplied on a daily basis. Streamflow routing models require additional detailed information about soil properties and basin geomorphology. Models often require extensive calibration in order to validate parameters for specific regions. How then can hydrological modeling be used for day-to-day management of nonexperimental areas?

A good example of how to achieve such a goal is supplied by the WRENSS procedure. The remainder of this presentation will focus on the development and application of WRENSS for the prediction of water yield increases following harvesting.

The acronym WRENSS comes from the title of a handbook entitled *Water resources evaluation on non-point silvicultural sources* (United States Department of Agriculture, Forest Service 1980). The handbook was developed by USDA Forest Service hydrologists, and it assembled easy-to-follow procedures for predicting the magnitude of various effects of land use on water quantity, quality, and timing. In the more limited scope of this presentation, WRENSS refers to Chapter 3 of the handbook that deals with the estimation of seasonal ET. For the past few years, an ever-improving programmed version of this procedure has been offered by the Northern Forestry Centre's forest hydrology and microclimate project, with a few minor adaptations to our northern conditions. The latest version of the programmed WRENSS, for IBM PCs and compatibles, is available from the Centre.

The WRENSS procedure is a simple method for estimating ET of a parcel of land using a minimal number of inputs. It is not a model but the result of the application of models. It permits the estimation of seasonal ET for different regions, under different forest cover types, densities, and harvesting intensity and patterns. It makes possible the routine prediction of the effects of deforestation or afforestation on the average annual water yield of ungauged basins.

How Was WRENSS Developed?

The first step in the development of the WRENSS procedure was the division of the United States into seven forested areas of similar climate. These regions are shown in Figure 1 along with their possible Canadian extensions. Many experimental basins were then selected in each region, and one of two water-balance models was fitted to their streamflow and meteorological data. In the regions with major winter snowpack, the model used was WATBAL (Leaf

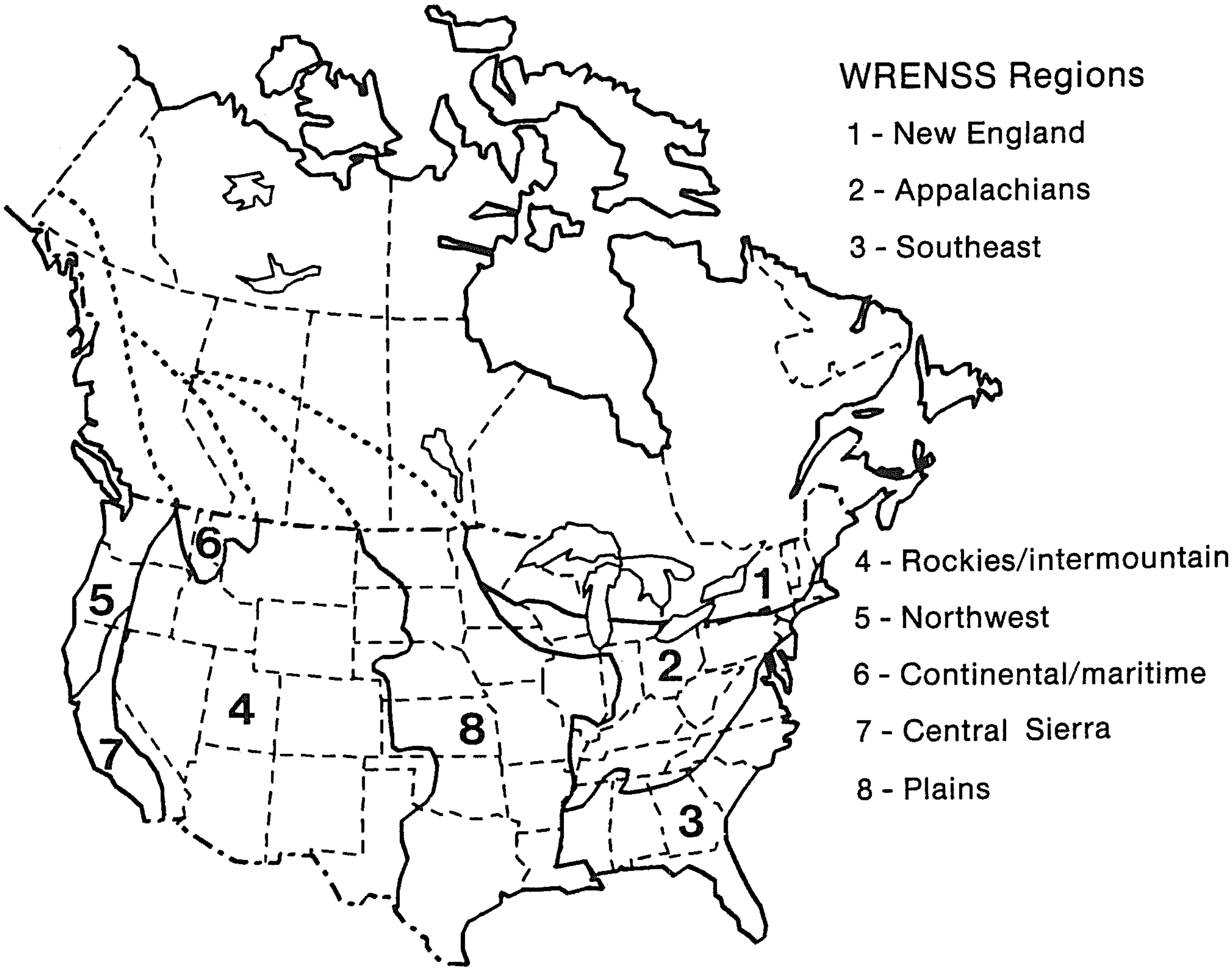

Figure 1. Hydrological regions defined for the development and application of the WRENSS procedure in the United States, and their possible extension into Canada.

and Brink 1973b), a model that has a snowmelt simulator as its core. For regions where there was no snow or where snowmelt did not dominate the hydrological picture, the model used was PROSPER (Goldstein and Mankin 1972), a model centered on the mechanistic description of water movement in trees.

Simulations were first carried out on the baseline, or unaltered, condition of the experimental basins, using as many years of data as were available. Once this was done and the calibration was satisfactory, variables representing cover density, precipitation, and aspect of the basins were changed one at a time over a predetermined range, and the simulations were redone. Curves and coefficients relating ET to precipitation and to percent cover density were extracted by season, aspect, and region from all of these simulations. The resulting set of curves, the WRENSS procedure, is therefore an intricate table for simulation results, not a model. This distinction between procedure and model is very important because unlike models, WRENSS cannot be "calibrated" to a specific basin without going back to the original models themselves.

What Does WRENSS Require as Inputs?

Inputs for WRENSS can be divided into four groups. The first group, the geographical description of the land, includes the WRENSS region in which the basin is located, its area, and its aspect. The second group is the meteorological description of the unit. Precipitation is entered as totals per season. The WRENSS seasons do not correspond to calendar seasons but rather to portions of the year with similar hydrological behavior. Two other variables, length of winter in days and average wind speed, were added by us at the Northern Forestry Centre to better represent snow processes.

The third group is the stand description, with vegetation type, actual basal area, and maximum basal area of the stand expected at maturity. The fourth group, treatment description, requires the nonforested area of the unit, the average size of the openings, the height of the trees in the forested portions of the unit, and the average height (roughness) of debris and brush in the opening.

What Does WRENSS Give as Output?

The WRENSS procedure gives "seasonal" net precipitation and an estimation of ET for both the forested and nonforested portions of the basin, and, by difference, water yield. Because the WATBAL model is a water balance model only, WRENSS does not really compute streamflow but rather generated runoff (GRO), water that will sooner or later become streamflow but has not yet been routed through the ground.

The effect of forest cover modification can be computed from successive runs through the procedure. After computing GRO for an undisturbed basin, one can then compute the GRO of the same land area with various levels of afforestation or deforestation. The difference in GRO gives an estimate of treatment effect.

Example of Results

The following examples were produced by Robert Swanson of the Northern Forestry Centre as part of a series of lectures sponsored by the Canadian Water Resources Association. Figure 2 shows predicted against measured water yield increases following harvesting on four experimental basins (see Bates and Henry 1928, Troendle and Leaf 1981, and Swanson et al. 1986 for most of the original data). Percent cut ranged from 21% on Cabin Creek to 100% on Wagon Wheel Gap. Area of the cuts, an important parameter for the computation of snow evaporation, ranged from less than 1 ha for Fool Creek to about 80 ha for Wagon Wheel Gap. As can be seen, the effect of timber harvesting on water yield on the four basins was quite different. Both Fool Creek and Wagon Wheel Gap data were used in the development of WRENSS, so a good fit to the data from these two basins is not unexpected. Data from Cabin Creek and Streeter provide an independent test of the procedure.

CONCLUSION

These few examples of hydrological applications to forestry do not exhaust the field. One needs only to think of forest drainage, water logging following harvest, or even irrigation in nurseries to see other areas where hydrological knowledge is essential. Forestry is moving increasingly away from a forest harvesting-only operation toward more-integrated forest management. In such a context, hydrological knowledge, whether or not through modeling, will help managers make better decisions for both the water and the timber resource. In the area of estimation of water yield increases following harvesting, a model-based procedure is now available to forest managers. Models exist in other areas, but these are not suitable yet for easy and routine management application.

Finally, we should not think that water stress in trees is limited to low rainfall areas. Newly planted seedlings in clear-cuts can be subjected to debilitating water stress even during a short drought. Agriculture on the prairies has learned how to manage the vegetation to enhance water availability to the plant. Through hydrological studies and models, forestry can do the same and increase the survival and growth of seedlings and trees.

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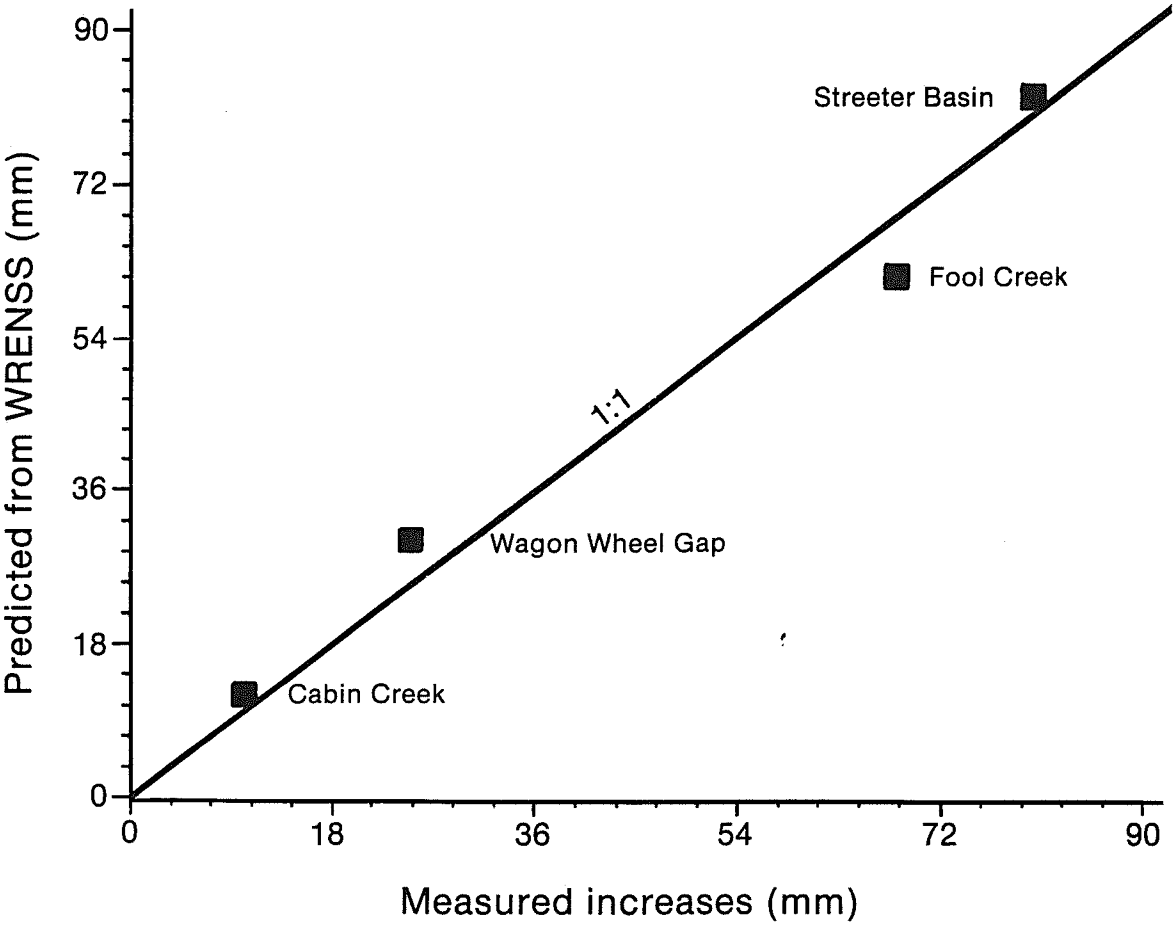

Figure 2. Predicted versus actual water yield increases following harvest on four experimental basins of west-central North America (analysis by R.H. Swanson).

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