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A comparison of mapped estimates of long-term runoff in the northeast United States

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Abstract

We evaluated the relative accuracy of four methods of producing maps of long-term runoff for part of the northeast United States: MAN, a manual procedure that incorporates expert opinion in contour placement; RPRIS, an automated procedure based on water balance considerations; PnET-II, a physiologically based model of carbon/water balance in forests; and MAPSS (Mapped Atmosphere–Plant Soil System), a rule/process-based vegetation distribution/water balance model. Our goal was to confirm the accuracy of the modeling and mapping procedures, and to see if any improvements to the models and methods might be suggested.

In our analyses, we compared contour maps derived from the four methods both qualitatively (visual inspection) and quantitatively (raster overlay and uncertainty analysis). The manual and automated (RPRIS) methods gave the best results. Our analyses suggest that methods directly integrating gaged runoff data (i.e. MAN and RPRIS) provide the best results under current climatic conditions. For predicting runoff under altered conditions, e.g. climate change, the existing models studied here (i.e. PnET-II and MAPSS) hold significant promise.

Keywords: Runoff mapping; Runoff modeling; Water balance model; Precipitation

1. Introduction

The distribution of runoff (i.e. runoff-depth) has been represented by various methods ranging from maps produced manually (e.g. Domokos and Sass, 1990; Krug et al., 1990) and by automated procedures (e.g. Solomon et al., 1968; Foyster, 1975), to the output of complex models (e.g. Aber et al., 1995; Neilson, 1995). Runoff maps have proven to be useful tools in water resource planning (e.g. Solomon et al., 1968) and in regional scientific studies (e.g. Rochelle and Church, 1987; Mattson et al., 1997).

Bishop and Church (1992, 1995) recently developed automated (i.e. non-manual, Geographic Information System-based) procedures to produce runoff maps, based on water balance considerations, that meet or exceed the accuracy of manually produced maps. Aber et al. (1995) produced a regional estimate of runoff for forested areas as part of a climate change analysis for the northeast (NE) United States with their water balance and carbon gain

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model, PnET-II. Neilson (1995) produced a map of runoff for the conterminous US as part of his continental scale model of vegetation distribution, the Mapped Atmosphere–Plant Soil System (MAPSS). In this paper, we examine how runoff maps produced by a manual method (Krug et al., 1990), MAN, and by one of the automated methods of Bishop and Church (1995), RPRIS, might compare to the output of these complex models. Possible future climatic changes in runoff amounts and patterns are a concern for society at large. Cross-validation of runoff estimates produced by these diverse methods would help to confirm the accuracy of the modeling and mapping procedures involved, and might give us a sense of the level of confidence that we can place on predictions of future conditions by these models. We also wondered if comparing the spatial patterns of the various maps and statistical results might suggest possible improvements in model formulations.

The maps presented and analyzed here can be divided into two classes: (1) data-based (direct estimation); and (2) process-based (indirect estimation). The manual and automated mapping methods require gaged runoff and other data from within the mapped area. In their present form, these methods are not suitable for mapping runoff under altered climatic conditions. The MAPSS and PnET-II models estimate runoff as a by-product of vegetation processes (the models main emphasis) and do not require runoff gage data. The MAPSS model is calibrated to produce predictions consistent with measured runoff and general vegetation classes at a few specific locations within the continental US, and is then applied to areas beyond the calibration domain (Neilson, 1995). The PnET-II model predictions are based solely on the representation of physiological and ecosystem processes within the model. These processes are defined through empirical constructs. In this work, we made no effort to adjust parameters in either model to achieve an acceptable fit for our regional application. Table 1 summarizes the methods examined in this paper.

To help maintain intercomparability between model results, we used precipitation estimates produced by the Precipitation-elevation Regressions on Independent Slopes Model (PRISM) (Daly et al., 1994) at a 10 km pixel resolution to drive both models. The models have no other data inputs in common. We also used PRISM estimates for the automated method RPRIS. The geographic extent of the application of PnET-II is the NE (Fig. 1), thus our study is restricted to this region.

Table 1
Comparison of methods used to estimate and map runoff

Estimation method	Input	Approach	Literature reference
MAN	Gaged runoff Precipitation patterns	Expert knowledge used to place contours	Krug et al., 1990
RPRIS	Gaged runoff PRISM precipitation	Estimated runoff/precipitation are applied across the region to estimate runoff	Bishop and Church, 1995
PnET-II	Mean maximum and minimum temperature PRISM precipitation Solar radiation Forest type Soil water holding capacity	Physiologically based model of carbon/water balance in forests	Aber et al., 1995
MAPSS	Mean temperature PRISM precipitation Vapor pressure Wind speed Digital elevation model	Rule/process based vegetation distribution/water balance model	Neilson, 1995

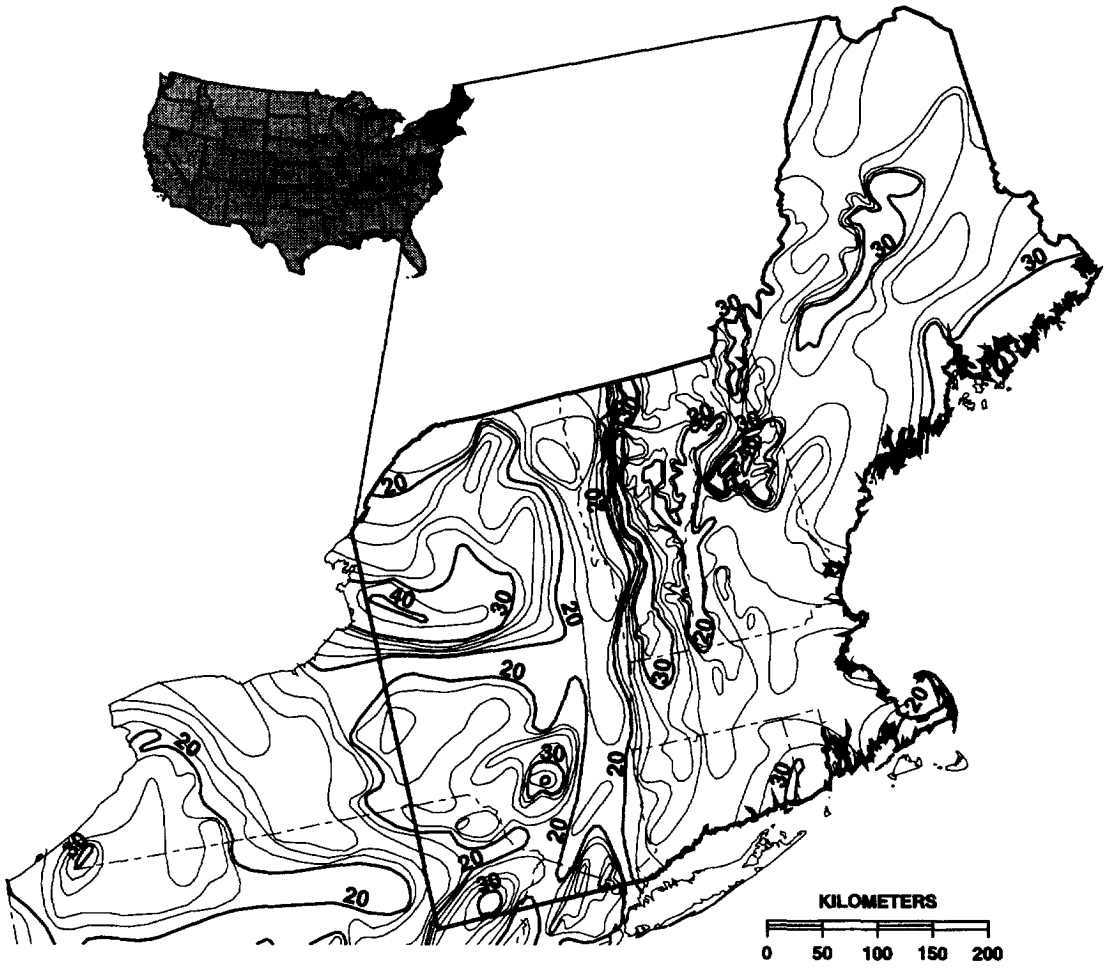


Fig. 1. Map of long-term (1951–1980) runoff for the extent of the PnET-II model in the northeastern United States (source: Krug et al., 1990). Contour interval: 2 inches (5.08 cm) below the 30 inch (76.2 cm) contour, 5 inches (12.7 cm) above the 30 inch (76.2 cm) contour.

2. Models, data and mapping methods

2.1. PRISM

PRISM is an analytical model that uses point observational data and a digital elevation model (DEM) to generate grid estimates of monthly and annual long-term mean precipitation (Daly et al., 1994). Observational data came from approximately 7000 National Weather Service and cooperator precipitation stations, and 500 SNOTEL (Snow Telemetry) stations across the conterminous US (USDA Soil Conservation Service, 1988). Results from PRISM were used in the RPRIS method, and as input to the PnET-II and MAPSS models.

The main simplifying assumptions of PRISM are: (1) on a local hillslope, the spatial variation of precipitation is primarily controlled by elevation; (2) the relationship between precipitation and elevation (P/E function) is best described when the elevations of the station data are expressed at a spatial scale that matches the scale of the precipitation processes reflected in the data; and (3) precipitation patterns over a mountainous landscape can be modeled by dividing the terrain into a mosaic of topographic faces, or 'facets', each assumed to possess a different

P/E function. By using P/E relationships uniquely developed within local windows around each grid cell, rather than a single domain-wide relationship, PRISM continually adjusts its frame of reference to accommodate local and regional changes in the orographic regime.

Phillips et al. (1992) and Daly et al. (1994) compared PRISM to kriging, detrended kriging, and co-kriging precipitation estimates in the Willamette River Basin, Oregon. They found that PRISM had the lowest overall bias and mean absolute error.

The NE PRISM dataset is a subset of a 10 km pixel resolution PRISM map encompassing the lower 48 states. Daly and co-workers prepared this map in 1992, largely in support of MAPSS and related modeling efforts.

2.2. Modeling and mapping procedures

2.2.1. Manual mapping procedure

Krug et al. (1990) mapped long-term runoff for the eastern US at a scale of 1:3 168 000. They used plotted gage data, placed at the centroid of each watershed, and the subjective consideration of precipitation patterns and other geographic considerations to manually construct their contours. A review of the map by state and other hydrologists was an integral part of the process. We have given this map the shorthand name 'MAN'.

2.2.2. Data used in manual mapping

In producing the manual map, Krug et al. (1990) used runoff data for the long-term period (1951–1980) from 1230 US Geological Survey (USGS) gaged sites in the eastern US (316 of the sites are in the NE study region). If a site was not in operation during the entire 30-year-period, Krug et al. performed additional analyses to create a long-term average runoff estimate for it. The sites represent watersheds ranging in size from less than 1 to nearly 4120 km^2, and do not include any basins with large or unquantifiable diversions (Krug et al., 1990).

2.2.3. Automated mapping procedure

We used the RPRIS method of Bishop and Church (1995) to create the automated procedure map considered in this study. This method was developed to provide a relatively simple means of producing runoff maps that are as/more accurate than the manual method, as well as having the advantage of being reproducible. The RPRIS approach used PRISM estimates of precipitation at the centroids of gaged watersheds to calculate runoff-to-precipitation ratios (R/P). These values were then used to create a surface of R/P using an inverse distance-weighted algorithm (Environmental Systems Research Institute—ESRI, 1991). This R/P surface was then applied to the PRISM precipitation surface to generate the estimated runoff surface for contouring (i.e. R = P*R/P). Bishop and Church (1995) give a more detailed description of the RPRIS procedure.

2.2.4. Data used in automated mapping

In producing the automated procedure map, we used the gaged USGS runoff data described above in Section 2.2.2, as well as the long-term average 10 km resolution PRISM output described in Section 2.1.

2.2.5. The PnET-II model

PnET-II (Aber et al., 1995) is a lumped-parameter model that uses generalized physiological relationships validated at the canopy level (Aber et al., 1996), and a limited number of vegetation and site-specific parameters, in conjunction with monthly climate data, to calculate monthly water and carbon balances for forest ecosystems. The core relationships are data-based interactions: (1) between foliar nitrogen concentration and maximum net photosynthesis; and (2) between realized photosynthesis and foliar conductance. These relationships allow for the simultaneous prediction of carbon gain and water loss based on measured N status (foliar N concentration) of vegetation. The water balance routine uses a simple bucket model for soil drainage calculations, and reduces both photosynthesis and transpiration when the ratio of potential evapotranspiration to soil water content exceeds a specified soil water release parameter. Currently, the PnET-II model is run with a pixel resolution of ~1.8 km.

Aber et al. (1995) developed the PnET-II model with the aim of capturing the physiological and ecosystem-level feedbacks necessary to assess the effects of multiple environmental stressors on plant function and runoff (water yield). The model is based entirely on processes involving carbon, nitrogen, water and

energy, and is thus subject to the limitations of current understanding of those processes. It has been used to predict forest response to climate change and elevated CO_2 (Aber and Federer, 1992; Aber et al., 1995), tropospheric ozone (Ollinger et al., 1996), and nitrogen deposition (Aber et al., 1997).

Potential Evapotranspiration (PET) in PnET-II is computed as potential (non-water limited) photosynthesis in any month, multiplied by water use efficiency. Potential photosynthesis is a function of LAI, maximum photosynthetic rate of foliage (in turn a linear function of foliar N concentration), and climate conditions (temperature, radiation). Water use efficiency is the product of an empirical constant times vapor pressure deficit (VPD). This is one of the unique aspects of PnET-II, in that it does not use the traditional Penman–Montieth or Thornthwaite energy-balance approaches, but calculates PET as a function of photosynthesis—a biotic rather than physical control.

The water balance in PnET-II is not calibrated in any way. Actual evapotranspiration is calculated from PET using a water stress term based on a soil water release function taken from the BROOK model of Federer and Lash (1978). Precipitation inputs are reduced by canopy interception (a specified fraction of deposition). Precipitation is partitioned between rain and snow based on air temperature. Snow melt also occurs as a function of temperature. A specified fraction of the water entering the soil compartment is lost as fast flow and the rest is added to plant-available soil water. This is drawn down by transpiration and any water remaining at the end of the month beyond a specified water holding capacity is lost to drainage. Data for this algorithm are taken from the literature, and are not altered in response to predictions or constrained in any way by runoff data. For water balance calculations, the change-in-groundwater component is assumed to be zero (over the long-term).

The PnET-II model requires 16 vegetation and site-specific input parameters. Many of these parameters can be generated from simpler data, e.g. forest type. Sensitivity analyses show that those parameters relating to maximum photosynthetic rate (e.g. the relationship between foliar N and maximum photosynthesis) are by far the most important in determining predicted carbon and water balances.

PnET-II has been validated against several measures of ecosystem function, including monthly carbon balances (Wofsy et al., 1993; Aber et al., 1995) and annual foliar and wood production at the Harvard Forest (Magill et al., 1997), and monthly streamflow (Federer et al., 1990) and annual foliar and wood production (Gosz et al., 1972; Whittaker et al., 1974) at the Hubbard Brook Experimental Forest. Complete descriptions of model algorithms, parameters and validations are presented by Aber and Federer (1992), and Aber et al. (1995, 1996).

2.2.5.1. The PnETP map. Producing a contour map based on the ~1.8 km resolution PnET-II runoff for the visual comparison (described in Section 3.1) and the uncertainty analysis (described in Section 3.3) was problematic. Exclusion of the non-forest pixels of our study area would have produced contour maps with unrealistic contour patterns and would have prevented the use of several of the gaged sites used in the uncertainty analysis. We chose to use an inverse distance weighting algorithm to interpolate runoff estimates from forest to non-forested pixels. Linear interpolation was then used to convert this modified version of the PnET-II output into a contour map. We gave this map the shorthand name 'PnETP' to clearly distinguish it from the unmodified PnET-II estimates used in the raster analysis (Section 3.2). To test for any bias in the forest versus non-forest areas of the PnETP map, we compared gaged runoff data to estimates made from the PnETP maps at gaged runoff watershed centroids. No significant bias is evident ($P < 0.05$) for the difference between actual and estimated runoff values at forest versus non-forest sites. Because the watersheds used in this test include a mixture of forest and non-forest areas, this test is not conclusive in itself. The possibility of an introduction of bias by propagating the forest runoff estimates to non-forested areas therefore exists.

2.2.6. Data used in PnET-II

Running PnET-II regionally required maximum and minimum daily temperature, precipitation and solar radiation values, all at a monthly time step. The model also requires estimates of forest type and plant-available soil water-holding capacity (WHC). Average monthly precipitation inputs were derived from PRISM (see Section 2.1). Other climate inputs

(e.g. mean solar radiation) were generated using a simple statistical model developed from long-term (1951–1980) climate records (Ollinger et al., 1995). Forest types were determined from a land use/land cover map (LULC), developed for the northeast region by Lathrop and Bognar (1994) using AVHRR (Advanced Very High Resolution Radiometer) satellite data. This map identifies hardwood, spruce fir, mixed hardwood/spruce fir and mixed hardwood/pine forest types, and a number of non-forest categories at 1 km resolution. Approximately 70% of the region is classified as forest (Lathrop and Bognar, 1994). Aber et al. (1995) describe the vegetation-specific input parameters. Foliage nitrogen content is the most important of these parameters because it determines the maximum rate of photosynthesis and thus influences potential transpiration. Because regional-scale foliar N data are not available, a single value of foliar N was assigned to each forest type identified in the LULC map (Aber et al., 1995).

In the absence of a successfully validated plant-available soil WHC map for the northeast region (Lathrop et al., 1995), PnET-II was run with a WHC value of 12 cm, representing a typical sandy loam soil with a rooting depth of 1 m and 25% coarse fragments.

PnET-II was run at a resolution of 1 arc min (~1.8 km) and later coarsened (10 km resolution), resampled (means), and projected into the Albers equal area projection for the pixel-based comparison with the other maps. Because PnET-II does not simulate the function of non-forested ecosystems, it was not applied to grid cells classified as non-forest in the LULC map. This is an important difference between PnET-II and other methods.

2.2.7. *The MAPSS model*

MAPSS is a global biogeography model that simulates the potential natural vegetation that can be supported at any upland site in the world under a long-term steady-state climate. The model operates on the fundamental principle that ecosystems tend to maximize the leaf area that can be supported at a site by available soil moisture or energy (Woodward, 1987; Neilson et al., 1989; Neilson, 1993; Neilson, 1995). Neilson developed MAPSS with the minimum hydrologic structure that would allow for a single calibration of the model to be applied to all of the very different hydrologic regions of the conterminous US.

The model calculates the leaf area index (LAI) of both overstory (tree or shrub) and understory (grass) life forms in competition for both light and water, while maintaining a site water balance consistent with observed runoff at a small number of locations in disparate regions of the US (Neilson, 1995). Water in the surface layer is apportioned to the two life forms in relation to their relative LAIs and stomatal conductances, i.e. canopy conductance. Only woody vegetation has access to deeper soil water in the model. Given sufficient energy, the LAI of the overstory and understory layers is calculated iteratively such that available water is nearly, but not entirely, depleted at some time during the year.

The MAPSS model uses a physiologically conceived rule-base to determine the dominant leaf form (broadleaf, needleleaf), leaf phenology (evergreen, deciduous), and thermal tolerances. These characteristics are then combined with the simulated LAI of the overstory and understory (produced from light and water competition) to produce a vegetation classification consistent with the biome level (Neilson, 1995). For our NE study region, MAPSS classified all lands as being forested.

The principal hydrologic features of MAPSS include algorithms for: (1) formation and melt of snow; (2) interception and evaporation of rainfall; (3) infiltration and percolation of rainfall and snowmelt through three soil layers; (4) runoff; and (5) transpiration based on LAI and stomatal conductance. For water balance calculations, the change-in-groundwater component is assumed to be zero (over the long-term).

Infiltration and percolation (saturated and unsaturated) are represented in MAPSS by an analog of Darcy's Law, specifically calibrated to a monthly time step. Water holding capacities at saturation, field potential and wilting point are calculated from soil texture and depth, as are soil water retention curves (Saxton et al., 1986). Transpiration is driven by PET, as calculated by an aerodynamic turbulent transfer model based upon the Brutsaert (1982) ABL model (Marks, 1990b; Marks and Dozier, 1992), with actual transpiration being constrained by soil water, leaf area and stomatal conductance. Stomatal conductance is modulated as a function of PET (a

surrogate for vapor pressure deficit) and soil water content (Denmead and Shaw, 1962). Canopy conductance (i.e. actual transpiration) is an exponential function of LAI, modulated by stomatal conductance.

MAPSS was calibrated for runoff at ~10 stations located in the states of Alabama, Illinois, Nebraska and Oregon. After this universal calibration, MAPSS was implemented at a 10 km resolution over the conterminous US and at a 0.5° resolution globally (Neilson, 1993; Neilson and Marks, 1994; Neilson, 1995). The model has been partially validated within the US and globally with respect to simulated vegetation distribution, LAI, and runoff (Neilson, 1993; Neilson and Marks, 1994; Neilson, 1995).

We used linear interpolation to convert the raster MAPSS estimates into a contour map used in the visual comparison and the uncertainty analysis. We gave this map the shorthand name 'MAPSS'.

2.2.8. Data used in MAPSS

The MAPSS model was run on a gridded dataset of mean monthly precipitation, temperature, vapor pressure and wind speed that encompasses the conterminous US. All of the MAPSS data input layers are based on a 10 km resolution DEM (Marks, 1990a). Precipitation estimates came from PRISM (described in Section 2.1). We present below a brief overview of the approaches used for the remaining variables. Marks (1990a) presents a full discussion of the methods used in the MAPSS model.

Monthly average air temperatures for the years 1948–1987 were calculated for 1211 stations in the conterminous US from the Historical Climatology Network database (Quinlan et al., 1987; Karl et al., 1990) using the dry adiabatic lapse rate and a simple linear inverse distance-squared algorithm (Isaaks and Srivastava, 1989).

Gridded vapor pressure data were derived from the interpolation of relative humidity from National Climatic Data Center and the World-wide Airfield Summaries databases (Spangler and Jenne, 1989) using the gridded temperature dataset and a simple linear inverse distance-squared algorithm (Isaaks and Srivastava, 1989).

Wind speed estimates were derived from a gridded US Department of Energy wind speed dataset described by Elliot et al. (1987). These wind speed estimates are based on a combination of surface measurements and upper air data accounting for topographic effects. The original 1/3 × 1/4° latitude–longitude grid was resampled using an inverse distance-squared algorithm (Isaaks and Srivastava, 1989). Winds were not corrected for the greater topographic detail available in the 10 km DEM grid.

Soil texture data are based on the soils map of Kern (1995) and the regression equations of Saxton et al. (1986), which convert soil water content to soil water potential.

2.2.9. Interpolation methods

We used linear interpolation based on Triangular Irregular Networks (TIN) to create all of the non-manual contour maps. TIN represent a given surface with a series of points of known values interconnected by triangular facets that represent a simplified version of the surface (ESRI, 1986). All of the non-manual maps produced for this study have a contour interval of 2 inches (5.08 cm) to maintain consistency with the manual map of Krug et al. (1990), which was produced in English units.

2.3. Comparison of methods

For the models examined here (i.e. PnET-II and MAPSS), the hydrologic processes important in the prediction of runoff include: (1) an atmospheric demand function, based on vapor pressure deficit (VPD) [as a minimum]; (2) canopy conductance, based on stomatal conductance, vertical LAI distribution and water-use efficiency; (3) soil water content, based on water supply, infiltration, percolation and transpiration; and (4) transpiration, based on atmospheric demand, vertical root distribution, soil water content and canopy conductance. Both MAPSS and PnET-II contain representations for all of these processes (Table 2). As such, both are process-based models. Within each of these processes, various empirical formalisms have been developed to represent the processes or different facets of the processes. The choices of empirical formalisms and their implementations vary however. Both models rely on the Beer's law approach to vertical canopy structure (LAI), and both constrain stomatal conductance based on VPD and soil water content (or water potential). The models differ in their approaches both to atmospheric demand and to soil

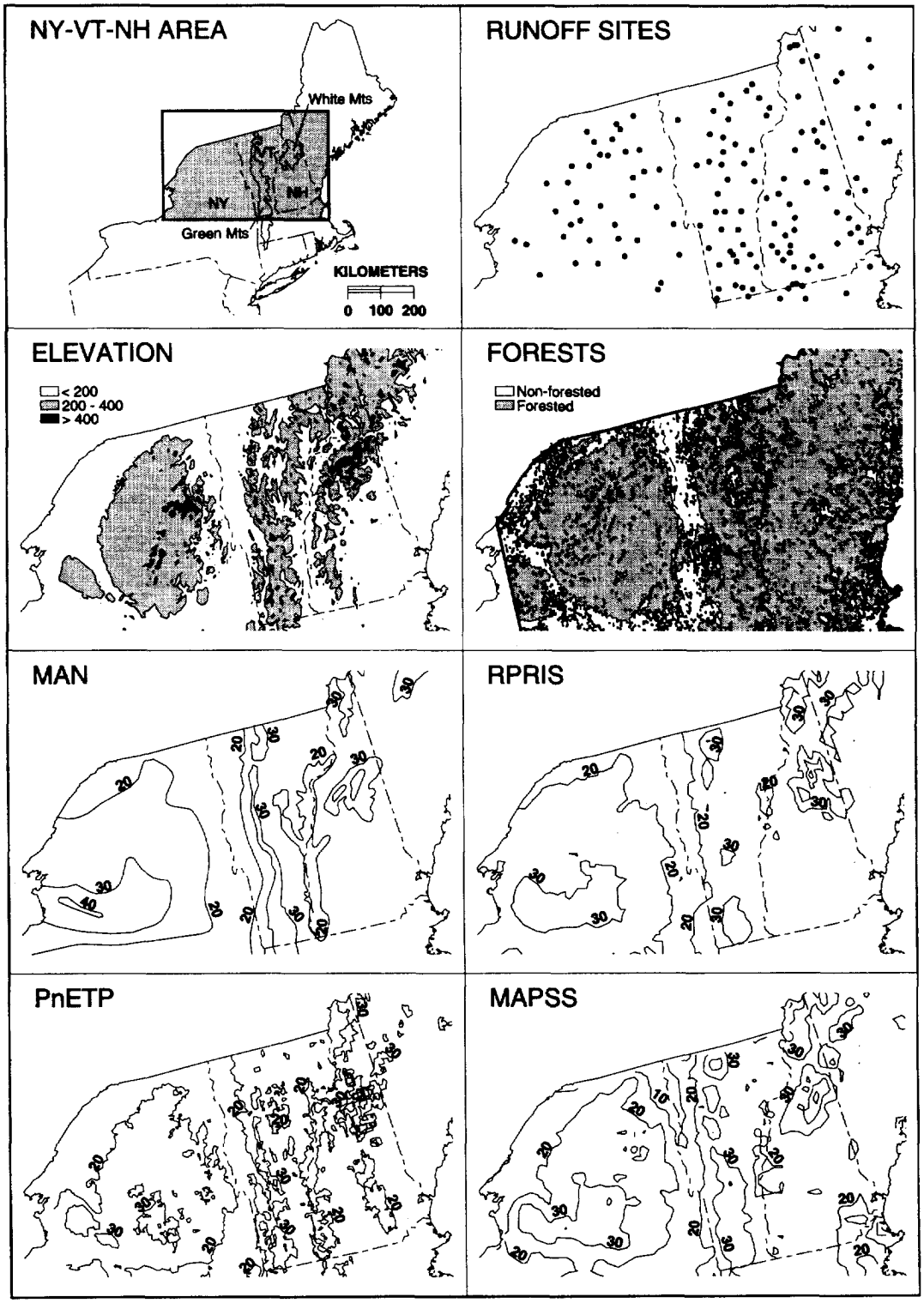


Fig. 2. Site and station locations, elevation and forest cover for the New York, Vermont and New Hampshire area, and long-term mean annual runoff for the four methods examined in this paper. Elevation contours: meters. Runoff contours: inches.

Table 2
Comparison of hydrologic processes modeled by PnET-II and MAPSS

Method	Atmospheric demand	Canopy conductance function	Soil water content	Transpiration
PnET-II	Vapor pressure deficit	Beer's law approach, constrain stomatal conductance based on VPD and soil water content	one soil layer, infiltration and percolation algorithms, bucket model (fast flow)	Empirical productivity constraints [energy (radiation) and N], process based
MAPSS	Vapor pressure deficit	Beer's law approach, constrain stomatal conductance based on VPD and soil water content	three soil layers, infiltration and percolation algorithms (variations on Darcy's law)	Empirical productivity constraints [energy (degree days), no N constraint], process/rule based

hydrology. The approaches of the two models to atmospheric demand rely on VPD, but differ in complexity. This is a very active area of research and is well recognized for its uncertainties, even with respect to theory. The MAPSS and PnET-II models differ in the number of vertical soil layers, and in the infiltration and percolation algorithms. Both models use empirical productivity constraints on transpiration, but they are more complex in PnET-II than in MAPSS. For example, PnET-II contains both energy (radiation) and nitrogen constraints, whereas MAPSS uses a degree day energy constraint, but contains no nitrogen constraint.

In contrast to the modeling approaches, the RPRIS method is very simple in structure. Only precipitation estimates via PRISM, gaged runoff and the relationship of gaged runoff to precipitation (R/P) at watershed centroids are required to estimate runoff across a region. The manual method is also simple in structure, but is much more labor intensive. It also has the drawback of being relatively unreproducible in that, given a set of data, different groups of expert hydrologists might map runoff with somewhat different results.

3. Results and discussion

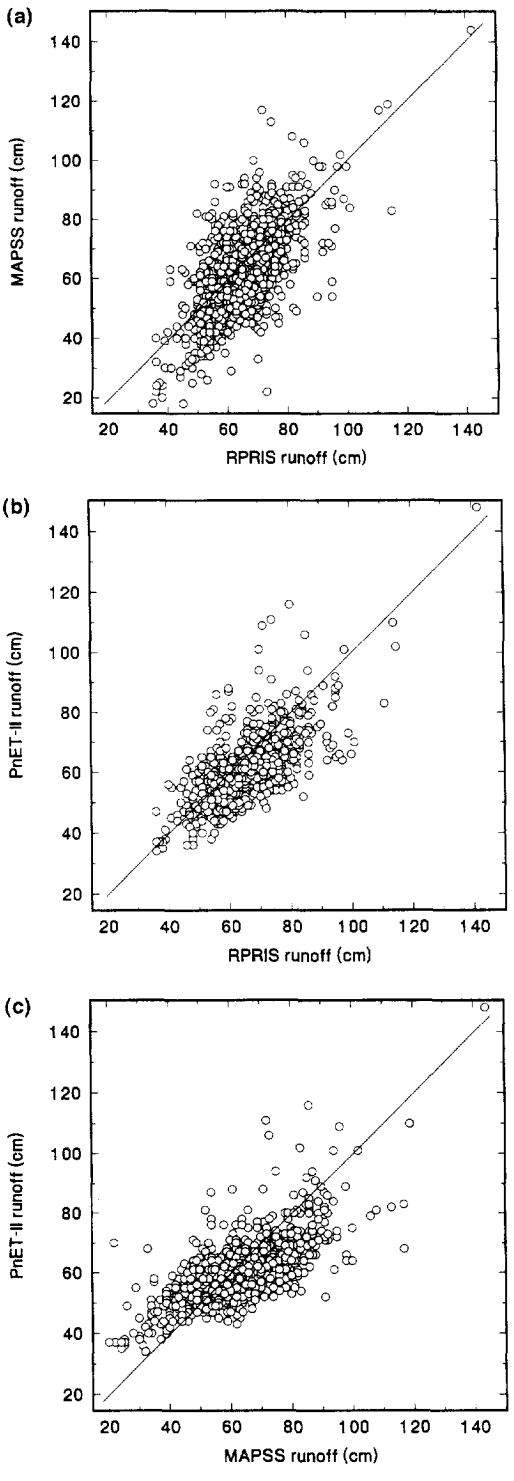
We incorporated three methods in comparing the manual and automated maps to the model results: (1) a visual comparison of the maps created by (or from the results of) each method; (2) a raster overlay analysis of three of the methods (RPRIS, PnET-II and MAPSS); and (3) a quantitative uncertainty analysis that compared interpolated estimates from the runoff maps with runoff at gaged watersheds withheld during the production of the maps.

3.1. Visual comparison

All of the maps in this study showed general agreement to the manual (MAN) map of Krug et al. (1990). Considering the variety of methods used in their creation, the good visual agreement was a pleasant surprise.

Some of the important differences and similarities in the maps can be seen in northern New York, Vermont and New Hampshire (Fig. 2). Variability among the different methods is in part due to the intrinsic scale of each method (i.e. MAN variable, PnETP 1.8 km, RPRIS and MAPSS 10 km). Examining the mapped runoff, we see that the PnETP map contains more fine spatial structure than the MAPSS or RPRIS maps, whereas the MAN map contains the least spatial structure.

In creating the contours for the MAN map, Krug et al. (1990) relied heavily on topography. All of the other methods take topography into account through the PRISM precipitation estimates, and thus produce contours consistent with the manual method. In general, the PnETP map has runoff values that are lower than the other methods, except in the White Mountains and Green Mountains (Fig. 2), where the values are similar or higher than the other methods. The higher runoff values for PnETP in this mountainous terrain may be due to the use of ~1.8 km resolution pixels. This finer resolution allows for the incorporation of more high-elevation (higher runoff) areas that are lost in the 10 km resolution-based methods due to generalization.



3.2. Statistical (raster) comparison of three runoff maps

We compared regional runoff estimates produced by RPRIS, MAPSS and PNET-II statistically on a pixel-by-pixel basis. There is no satisfactory means of estimating internal and external-contour pixel values from the MAN map, so it was excluded from this analysis. For this analysis, we assumed that the RPRIS map gives the best estimate of runoff in each pixel, using it as the basis for comparison to the other methods. This assumption is based on prior validation by Bishop and Church (1995) of RPRIS runoff against withheld data. Because the PnET-II estimates represent forested areas only, areas classified as non-forest in the Lathrop and Bognar (1994) land use/land cover map were not considered in this comparison. In aggregating (means) the PnET-II estimate to a 10 km resolution and screening non-forested areas from the RPRIS and MAPSS estimates, we used a majority-rule approach, such that areas containing less than 50% forest were omitted from the analysis. The omission of non-forested areas is expected to introduce a bias in regional mean runoff estimates because non-forested land in the northeast region tends to occur in lower elevation areas with lower precipitation and hence lower runoff (Lull and Sopper, 1966). The resulting maps contained a total of 1305 10×10 km pixels.

Comparison of the model predictions against RPRIS [Fig. 3(a)–(c), Tables 3 and 4] indicates considerable scatter and significant bias in both sets of model results. PnET-II shows lower maximum and minimum difference values than RPRIS (Table 4), with the mean for the region being 4.8 cm (7.4%) lower. MAPSS shows a wider range of extremes and is, on average, 3.5 cm (5.4%) lower than RPRIS. A Spearman correlation analysis gave correlation coefficient values of 0.61 for MAPSS versus RPRIS, and 0.67 for PnET-II versus RPRIS (0.65 for PnET-II versus MAPSS). Fig. 4 presents cumulative distribution functions of the differences in runoff between the three methods. Approximately 80% of the PnET-II pixel values are lower than the corresponding

Fig. 3. Scatter diagrams of runoff (cm) for the 1305 forested pixels in the study area of: (a) MAPSS versus RPRIS; (b) PnET-II versus RPRIS; and (c) PnET-II versus MAPSS.

Table 3
Statistical summary of pixel-by-pixel comparison (n = 1305); values based on forested areas of the region only

Method	Minimum (cm)	Maximum (cm)	Mean (cm)	Standard deviation (cm)	Standard error
RPRIS	36	142	64.5	9.9	0.27
MAPSS	20	144	61.0	13.2	0.36
PnET-II	34	148	59.8	9.4	0.26

RPRIS values, whereas ~70% of the MAPSS pixels have lower values than RPRIS.

Some of the biases exhibited by both the PnET-II and MAPSS estimates may result from differences in runoff between forested and non-forested lands. Although we omitted grid cells containing more than 50% non-forested land in this analysis, a substantial amount of non-forest exists in the remaining areas. Because runoff tends to be higher in non-forested than adjacent forested areas experiencing the same precipitation (e.g. Stednick, 1996), both PnET-II (which does not model non-forest land) and MAPSS (which modeled non-forested land in the NE as being forested) would be expected to underestimate the RPRIS values. The underestimation of RPRIS mean regional runoff by PnET-II and MAPSS is thus not surprising.

3.3. Uncertainty analysis

To assess the accuracy of the various runoff maps in predicting runoff at a given watershed, we conducted a quantitative uncertainty analysis. We used the techniques and a subset of the data used by Rochelle et al. (1989) and Bishop and Church (1995) in their analysis of runoff estimates made from long-term average runoff contour maps. The analysis consisted of estimating runoff by interpolation from the maps to the centroids of a set of gaged watersheds withheld from the creation of any of the maps to be tested, and then comparing the interpolated and actual gaged runoff values. Although Krug et al. (1990) found the area weighting method to be the most accurate method for estimating runoff for a given watershed from a runoff contour map, they found the difference in accuracy between the area weighting and the centroid method to be relatively small. Digital versions of the watershed boundaries used in this study are not available, so we used the simpler centroid method.

Rochelle et al. (1989) chose the withheld sites we used here by first creating regions of similar runoff and chemistry site density used in their study. They then selected the withheld sites using a weighting procedure based on runoff site density within each region. Rochelle et al. (1989) and Krug et al. (1990) provide more detailed descriptions of the methods used in selecting the sites. Because of the large differences in areas among the density regions, the summary statistics are based on weighted combinations of the regional estimates. Due to non-correspondence between the area covered by the PnET-II model and the density regions, we used a subset of the sites used by Rochelle et al. (1989) and Bishop and Church (1995). Area weighting and the number of sites in each region thus vary from these previous studies. Due to the robustness of the selection process, however, use of this subset does not bias the results (D. Stevens, personal communication).

Table 5 and Fig. 5 give the results of the uncertainty analysis. The MAN and RPRIS methods show the best

Table 4
Statistical summary of pixel-by-pixel differences between the RPRIS, MAPSS and PnET-II methods (n = 1305); values based on forested areas of the region only

Methods	Minimum (cm)	Maximum (cm)	Mean (cm)	Standard deviation (cm)	Standard error
MAPSS–RPRIS	−51	45	−3.5	9.9	0.27
PnET-II–RPRIS	−34	38	−4.8	7.6	0.21
PnET-II–MAPSS	−49	48	−1.3	9.4	0.26

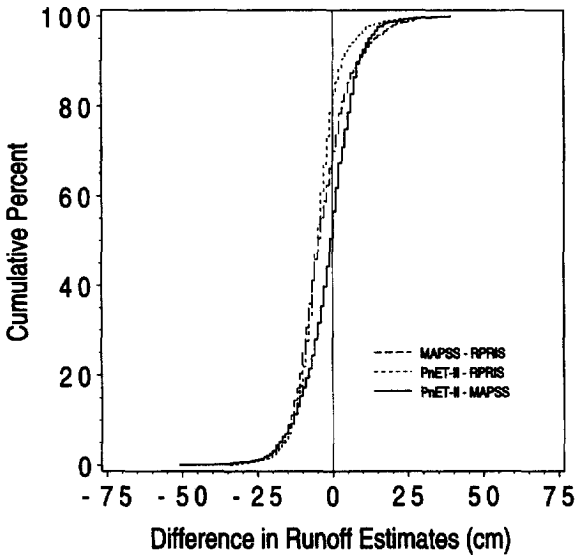


Fig. 4. Cumulative distribution functions of the pixel-by-pixel differences between runoff estimates.

results. These two procedures have low mean errors, and the lowest standard errors and standard deviations. MAPSS also has low mean errors, but has the highest standard errors and standard deviations.

We conducted a regression analysis to check for biases in estimated (interpolated) runoff as compared with actual runoff at the 31 withheld sites. For this analysis, the predictor variable is estimated runoff and the dependent variable is actual (gaged) runoff. A slope statistically equivalent to one and an intercept not significantly different from zero indicates a lack of bias. Table 6 shows the results of the analysis. PnETP is the only method that appears to be biased ($P < 0.05$). The MAN and RPRIS methods had the lowest standard errors and the highest R^2 values.

We examined cumulative distribution functions of the interpolation errors. Most interpolation errors were small and all of the procedures showed a marked increase in absolute interpolation errors towards the tails of their distributions. This pattern is consistent with that found by Rochelle et al. (1989) and Bishop and Church (1992, 1995) in similar studies. We analyzed the data for biases in interpolation errors versus watershed size and elevation with a Spearman correlation analysis. No biases ($P < 0.05$) were found.

4. Conclusions

We compared and evaluated long-term runoff, as represented by a manually derived map (MAN) and an automated procedure-derived map (RPRIS), to the output of two models. One of the models (PnET-II) estimates runoff as part of a water balance and carbon gain model (Aber et al., 1995). The second model (MAPSS) estimates runoff as part of a continental scale model of vegetation distribution (Neilson, 1995). Our evaluation of their relative accuracy is based on: (1) a visual comparison of contour maps derived from each procedure or from the models; (2) an overlay analysis of raster versions of three of the methods; and (3) an uncertainty analysis of deviations of runoff interpolated from contour maps from gaged runoff at 31 withheld sites.

Overall, we found the manual map of Krug et al. (1990) and the RPRIS map best represent current long-term runoff in the study region. This conclusion is based largely on the results of the uncertainty analysis. MAPSS performed reasonably well in the uncertainty analysis, but showed a small underestimation bias in a pixel-by-pixel comparison to the RPRIS map. Neilson (1995) noted a bias towards

Table 5
Area-weighted statistical summary of interpolation errors (interpolated minus gaged runoff) for the 31 withheld sites used in the uncertainty analysis

Method	Mean (cm)	Standard error (cm)	Standard deviation (cm)	Mean	(%) Standard error	(%) Standard deviation (%)
MAN	−1.4	1.01	5.64	−1.4	1.48	8.24
RPRIS	1.4	1.07	5.99	3.5	1.71	9.50
PnETP	−3.8	1.23	6.83	−4.8	1.86	10.34
MAPSS	0.3	1.39	7.72	2.0	2.55	14.17

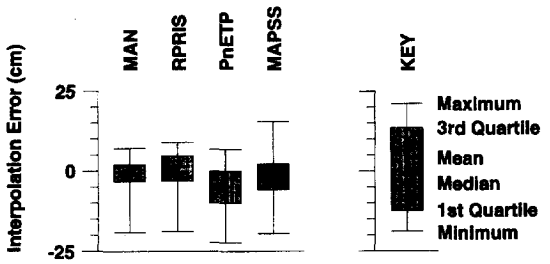


Fig. 5. Area-weighted interpolation errors (cm) for the 31 withheld sites.

underestimation of runoff with his model. He attributed this bias to his use of potential vegetation as opposed to actual vegetation, e.g. potential vegetation woodland (lower runoff) versus actual vegetation cropland (higher runoff). The uncertainty analysis found no bias towards underestimation by MAPSS. The PnETP map (based on PnET-II estimates) was found to be biased in the regression portion of the uncertainty analysis and showed an underestimation bias in a pixel-by-pixel comparison to the RPRIS estimates.

Model processes that could explain the differences in performance between MAPSS and PnET-II are the evaporative demand functions and the soil hydrology functions. Implementation issues, e.g. the use of a fixed soil WHC in PnET-II or a variable WHC based on texture and soil depth in MAPSS, could also be factors.

In the future, several of the individual parameters in PnET-II could be altered to increase the accuracy of the predictions produced. For example, the PnET-II estimates examined here were generated using fixed foliar nitrogen concentrations for each major forest type and a constant soil water holding capacity (12 cm). In all site-level validation exercises where measured values for these parameters were available, the model has performed well and has shown no apparent bias (e.g. Aber et al., 1995). We chose not to make alterations in the soil water-holding capacity and N concentrations given the current uncertainties in both of these input data planes. Such alterations would result in a calibrated model, with the implicit assumption that all the other variables in the model are correct. Future regional applications of PnET-II will include attempts to address the shortcomings of these data planes before considering any modification of the model. Expansion of the PnET-II model to non-forest areas might also help reduce the biases seen in this study.

Performance for the MAPSS model could probably be improved by using a more energy-based snow accumulation and melt module (which currently is temperature based), and by upgrading the relatively simple algorithms for: (1) canopy interception and evaporation; and (2) soil evaporation and infiltration. Changing the model from a monthly to a daily time step would undoubtedly improve the timing of runoff production, and allow a more physically based parameterization of the model. Incorporating current vegetation in MAPSS, as opposed to potential vegetation, when it is being used to predict current conditions might also improve its performance.

Improvement of the RPRIS method should be possible with finer resolution PRISM estimates and a denser, more spatially uniform gaged stream network.

Our work shows that the accuracy of runoff maps created from the output of the complex models examined approaches the level of accuracy of maps created by current manual and automated procedures. These modeling approaches hold promise for relatively accurate predictions of runoff under possible future environmental conditions.

Table 6
Statistical summary of the regression analysis comparing estimated with actual runoff (n = 31); estimated runoff is the predictor

Method	Slope	Standard error of slope	Intercept (cm)	Standard error of intercept (cm)	P^a	R^2
MAN	1.08	0.11	−3.30	6.84	0.337	0.76
RPRIS	1.19	0.13	−13.34	8.22	0.171	0.74
PnETP	1.36	0.17	−16.70	9.82	0.002	0.69
MAPSS	0.94	0.16	3.37	9.98	0.917	0.54

[a] P-value for the combined hypothesis test that the slope equals one and the intercept equals zero.

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