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Title: Analysis of Evapotranspiration for Various Climatic Regimes Using Geostatistics

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Research was conducted to determine the applicability of using the theory of regionalized variables or geostatistics in characterizing the spatial variability of reference evapotranspiration (ETr) over various climatic regimes for the state of Oregon. The state was divided into five climatic regions based on topographic features and local meteorological conditions: 1) Coast, 2) Willamette Valley, 3) Southwestern Valley, 4) North East, and 5) South East. The local ETr estimates provided from the FAO-modified Blaney Criddle method were divided into their respective regions and averaged over the three years.

The variogram analysis was performed on the average ETr estimates for May through September in each region. Model variograms were fitted to the calculated sample variograms and a cross validation routine performed to test the chosen model. For four out of the five subregions, a verified spherical model was obtained for the individual months. Difficulties related to the low number of samples representing the region made it difficult to confirm model variograms in region 3.

The model variograms determined for the average ETr estimates were used as the model variograms for the individual years (1985, 1986, 1987) to test the hypothesis that one model variogram could represent the spatial correlation of ETr for the region. Due to the inconsistencies seen in the analysis, no valid conclusions could be made to support this hypothesis. It is recommended that developing the model variograms from long term average ETr estimates instead of the short three year average could provide better results when applied to individual years.

Kriging was performed on the average ETr estimates for July and September in regions 1, 2, 4, and 5. From the kriging analysis, estimates of ETr along with the standard deviation over a grid representing the region were produced. Contour maps were plotted using the gridded information of kriged ETr and standard deviation of the kriged estimates. The results of these contour maps proved to be a good representation of the ETr estimates within most of the regions. It was noticed that the values of ETr of individual meteorological stations within the regions influenced the shape of the contour lines and the shape did not necessarily correspond to topographic effects in Oregon. One explanation is that the weather stations used for the ETr estimates are generally representative of the valleys in each region. For use in hydrologic modeling or irrigation system design and scheduling in valleys, the kriged ETr estimates could be very satisfactory. However, for use in large scale hydrologic modeling or global circulation models, a method to account for the topographic effects must be included in the kriged ETr estimates. A method that might prove successful is developing a spatial correlation between ETr and elevation through a geostatistical technique termed cokriging.

Another problem with the regional analysis was comparison at regional boundaries. To effectively utilize these contour maps for the whole state, there must be some method to deal with the transition zones between regions. A possibility is to combine kriged estimates from each region into one file representing the whole state and producing contour plots for the overall data file.

The use of geostatistics is becoming more common in hydrology and its use is expected to grow. From this work, geostatistics proved to be a possible tool to generate estimates and computerized plots of reference evapotranspiration (ETr). However, there are difficulties to overcome for geostatistics to be applied operationally in estimating regional evapotranspiration.

# Analysis of Evapotranspiration for Various Climatic Regimes Using Geostatistics

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# 1 INTRODUCTION

## 1.1 STATEMENT OF THE PROBLEM

The rate of evapotranspiration from the earth's surface is an important component in the hydrologic balance of the earth and has been of considerable interest and concern to scientists and engineers in the agricultural community since the 1950's. Accurate information on evapotranspiration rates is essential in irrigation management, hydrologic studies, crop management practices, and global climate models. In irrigated areas of the world, an increasing demand for water has stressed the importance in understanding the losses and use of water at scales ranging from local to regional.

With this increasing demand on the water supply, the agricultural community must take measures to insure an optimal use of this limited supply. Currently, designing an irrigation system and scheduling the amount and frequency of the water applied to a crop for a given region uses a locally estimated reference evapotranspiration rate from a weather station representative of the site. Reference evapotranspiration is a term used for evapotranspiration of a specific crop, usually grass, under a set of standard conditions. Doorenbos and Pruitt (1977) defined reference evapotranspiration (ETr) as " the rate of evapotranspiration from an extensive surface of 8 to 15 centimeters tall green grass cover of uniform height, actively growing, completely shading the ground, and not short of water." Local estimating scales for evapotranspiration are normally considered to be a radius of 10 km from the point of reference (Amegee, 1985). The region for which the irrigation system is designed or for which irrigation is scheduled may be considerably larger than what the weather station represents. This extrapolation of ETr from local estimating scales to a regional scale introduces errors which may cause crops to be overirrigated or underirrigated and an overdesign or underdesign of water storage reservoirs, wastewater treatment plants, and other systems relying on knowledge of regional evapotranspiration. Achieving an optimal use of the water supply for a given region requires an effort to improve the accuracy of regional ETr estimates and to quantify the error associated with the application of local ETr estimates to a region.

Another concern which has accelerated interest in the analysis of evapotranspiration on a regional scale is the attention to global climatic change. Regionalized evapotranspiration estimates are inputs to global circulation models (GCMs) used to predict both short-term and long-term climatic changes. These models normally operate on a minimum grid size ranging from 100 to 500 km (Cuenca and Amegee, 1987).

The combination of the increasing demand for knowledge which would improve the use and management of this limited water supply and recent concerns over global climatic change have encouraged and justified attempts to develop methods for analyzing or quantifing evapotranspiration on a regional scale. Developments in the field of remote sensing have suggested the potential for deriving regionalized estimates of evapotranspiration using the crop canopy temperature. This temperature is sensed by a satellite or other remote sensing instruments like the NASA C-130 aircraft, and is coupled with ground based measurements to model the evaporative flux from the earth's surface. Much of the technology in collecting the data exists and is well understood. However, the coupling of remote sensing data with ground based measurements to obtain accurate measurements of evaporative flux requires more research. Although the resulting formulas offer promising results, their validity has not been adequately verified with respect to soil moisture and cloudy sky conditions to allow operational estimates of regional ETr (Schmugge, 1978; Bernard et al., 1981).

A straight forward procedure (Baier, 1979) for estimating regional evapotranspiration consists of using local estimates over a small homogeneous area and applying a weighting factor according to the relative surface area. This particular method requires a large number of weather stations collecting data to achieve an accurate estimate of regional evapotranspiration. A desired method is to develop a model for ETr based on its spatial variability. Such a model would determine regional estimates of ETr based on the variation of ETr as a function of distance between available data points. This model would provide a more accurate estimate of ETr at locations where no climatic data are available compared to a method which does not take into consideration the structure of ETr variability (Amegee, 1985). The improved accuracy of estimated regional evapotranspiration would improve accuracy of irrigation systems, global circulation models, and be applicable to regional water resources development and management.

## 1.2 PREVIOUS WORK

In 1985, Kodjo Y. Amegee completed a Doctor of Philosophy in Civil Engineering with his thesis topic being application of geostatistics to regional evapotranspiration. Amegee studied how well the theory of regionalized variables could be applied to evapotranspiration. The findings of this research indicated that the spatial variability of reference evapotranspiration over large geographical areas could be described by model variograms and this information could be used to predict evapotranspiration rates by means of kriging (Amegee, 1985). Recommendations from this research suggested removing the bias associated with a model representative of the whole state of Oregon by deriving individual model variograms for climatic regions within the state.

## 1.3 OBJECTIVES AND SCOPE

This thesis presents an attempt to model regional evapotranspiration for various climatic regimes based on its spatial variability within each regime. The general objective was to compare the statewide regional ETr estimates computed by Amegee (1985) with an analysis of regional ETr estimates of five climatic regions using geostatistics. The project was a direct continuation of the research of Amegee (1985) into the application of geostatistics in estimating regional evapotranspiration. The specific objectives of this work were the following:

1. The first objective was to determine if an acceptable model variogram could be produced for the different climatic regions. A model variogram, defined in the next chapter, was fitted to the data of estimated ETr at different locations to relate the change in estimated ETr to the distance between stations. The data used to test this objective were derived by calculating the average monthly ETr for May through September from the three years (1985,1986, and 1987) of available data. The reason for using an average ETr from the three years is explained in the second objective.

2. The second objective was to observe if the model variogram developed for the average ETr could be used as the model variogram for the individual years. The purpose was to determine if a model variogram could be fitted to long term average ETr data then be used as the model variogram for ETr estimates gathered year to year, month to month, or week to week.

3. Assuming an acceptable model variogram could be produced for the individual months in each region, the last objective was to apply kriging to estimate reference evapotranspiration (ETr) over a grid of locations throughout the region and to produce contour maps of the regional ETr.

The scope of this project was limited to the state of Oregon. Estimations of reference evapotranspiration rates were made at 180 locations for 1985, 1986, and 1987 during the months of May through September. Within the state of Oregon, five climatic regions were identified. For each region, model variograms were developed for each month and year. These model variograms were used to krige reference evapotranspiration for a grid of locations throughout the regions. Contour maps of estimated ETr for each region were plotted.

# 2 LITERATURE REVIEW

This chapter is broken down into three main topics: description of evapotranspiration, local and regional evapotranspiration (ET) estimating methods, and fundamentals of geostatistics. The first topic gives basic definitions followed by a brief review of the methods used for the estimation of ET both on a local and regional scale. The last topic is a review of concepts in the theory of regionalized variables or geostatistics.

## 2.1 BASIC DEFINITIONS

Consistent definitions for evapotranspiration estimates are extremely important in maintaining communication within the research community. The following definitions are based on those found in the American Society of Civil Engineers (ASCE) report, "Consumptive Use of Water and Irrigation Water Requirements" (Jensen, 1974).

**Evapotranspiration**

Evapotranspiration is the loss of water from the ground to the atmosphere through water vaporization. The two main components making up evapotranspiration are water evaporated from the soil surface and water lost through plant surfaces which is termed transpiration. Figure 1 provides a schematic of the hydrologic balance in which a large role is played by evapotranspiration. As a global average, 57% of the annual precipitation falling over the land is returned to the atmosphere by evapotranspiration (Budyko et al., 1982). Evapotranspiration amounts to about 70% of the annual precipitation of the United States, and more than 90% in the arid areas of the Western United States, while it could be up to 100% in some desert areas (Hamon, 1966).

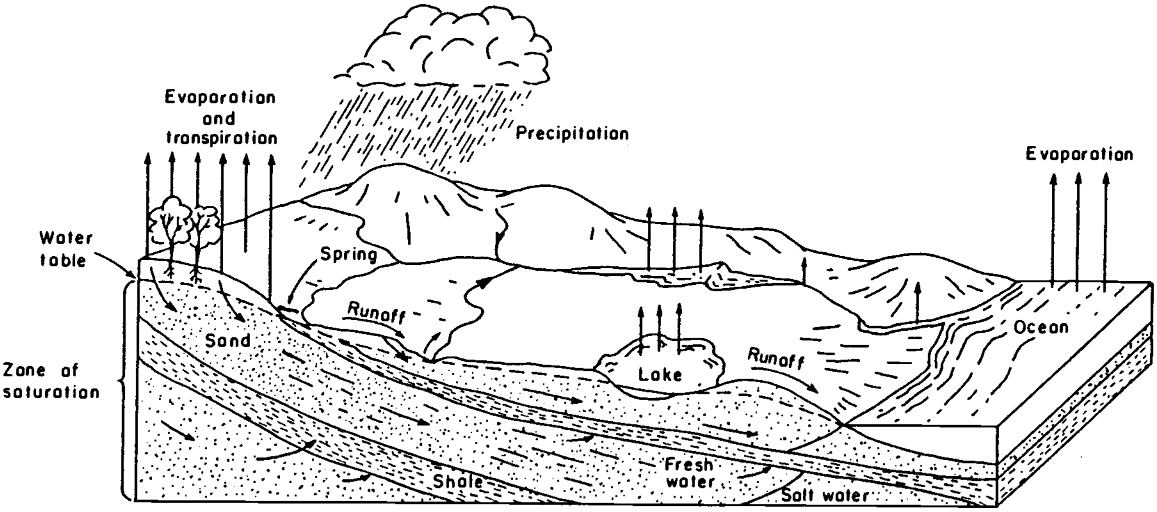



Figure 1: Schematic of the Hydrologic Balance (taken from Cuenca, 1989)

**Potential Evapotranspiration**

Potential evapotranspiration is the maximum rate at which water can be evaporated from the soil surface and transpired by a plant. Many researchers comment on the vagueness of this term. Due to this vagueness, a move to the term reference evapotranspiration has been occurring in many subject areas.

**Reference Evapotranspiration**

Two definitions are commonly used in defining reference evapotranspiration (ETr). Doorenbos and Pruitt (1977) defined it as "the rate of evapotranspiration from an extensive surface of 8 to 15 centimeters green grass cover of uniform height, actively growing, completely shading the ground, and not short of water". The second definition of ETr is from Jensen et al. (1971) and is defined as "the upper limit or maximum evapotranspiration that occurs under given climatic conditions with a field having a well watered agricultural crop with an aerodynamically rough surface, such as alfalfa, with 30 to 50 centimeters of top growth". Reference evapotranspiration in this work uses grass as the reference crop which corresponds to the definition provided by Doorenbos and Pruitt (1977).

## 2.2 REGIONAL VS LOCAL EVAPOTRANSPIRATION ESTIMATING METHODS

### 2.2.1 LOCAL EVAPOTRANSPIRATION ESTIMATING METHODS

An accurate account of methods for estimating ET from climatic data is not available, but the total must be in the dozens (Burman et al., 1983). The Penman equation (Penman, 1948) was introduced 41 years ago and is based on the combination approach of net radiation and a wind function. Much of the Penman equation is based on theory, however some form of empiricism exists to account for simplifications needed for practical use. Other more practical empirical methods exist and are widely used in water resource management and engineering projects.

Seventeen empirical methods were identified, examined, and compared by Erpenbeck (1981) at fourteen meteorological sites in the state of Washington. Seven of these methods used air temperature as the only weather parameter in estimating ETr. Air temperature is termed a primary weather parameter because of its common availability. Primary parameter refers to a parameter for which data are available for each day or month in each year. Ten of these methods used a combination of air temperature as the primary weather input plus secondary weather data on solar radiation, windspeed, and saturation deficit of the air. Secondary weather data are long-term averages of monthly data. The secondary weather data provide a means to adjust estimated ETr based on the general climatic conditions. Doorenbos and Pruitt (1977) concluded that one can improve ETr by applying local calibration or at least an adjustment that considers the general climatic conditions. These secondary data are typically available in a limited number of stations in a region.

Erpenbeck (1981) chose the Food and Agriculture Organization (FAO)- modified Blaney Criddle method (Doorenbos and Pruitt, 1977) as the best state-wide ET estimating method. The selection was based on the weather data available throughout the state of Washington and a statistical ranking using the coefficient of determination for each estimating method compared to lysimeter measurements. Another comparison among ETr estimating methods was performed by Allen and Brockway (1982). They selected the FAO-modified Blaney Criddle method as the best state-wide ET method based on accuracy and the primary data requirement of only air temperature. Allen and Brockway (1982) compared the Soil Conservation Service (SCS)-modified Blaney Criddle, the FAO-modified methods (i.e. FAO radiation, FAO-modified Blaney Criddle, FAO Penman, and FAO corrected Penman), the Jensen-Haise, standard Penman, and Wright modified Penman. The methods were evaluated using daily weather data from the USDA-ARS research center at Kimberly, Idaho (Twin Falls, WSO).

For the state of Oregon, Basketfield (1984) examined and compared two temperature-based ET estimating methods: the SCS modified Blaney Criddle (SCS-BC) and the FAO-modified Blaney Criddle (FAO-modified BC). Results indicated that the SCS-BC method seriously underpredicted crop ET at relatively high-altitude and semiarid locations (Basketfield, 1984). Basketfield selected the FAO-modified BC with adjustments developed by USDA to produce reference evapotranspiration, crop evapotranspiration, and irrigation requirements for selected Oregon locations. Comparison between Basketfield's estimates for ET and net irrigation requirements (NIRR) and those produced by Watt et al. (1968) for the state of Oregon led to recommendation of a revision of irrigation requirements for Oregon. The FAO-modified BC method with USDA adjustments was chosen for both the work performed in the revision and this thesis because the studies performed in Washington (James et al., 1982), Idaho (Allen and Brockway, 1983), and Oregon (Basketfield, 1984) indicated that this method would be more accurate than any other temperature-based method and make good use of temperature data available at many sites in Oregon. The following is a review of the FAO-modified Blaney Criddle method.

#### 2.2.1.1 FAO Modified Blaney Criddle Method

FAO provided funds to publish guidelines for predicting crop water requirements. The work was conducted by Doorenbos and Pruitt using data from 13 sites representing various climates around the world. The data used were meterological and lysimeter data provided by the United Nations. The work produced a modification to the original Blaney Criddle Method by estimating ETr using temperature as a primary weather parameter and adjusting for additional effects of local meteorological conditions by using general estimates or ranges of relative humidity, sunshine hours, and wind speed. Use of humidity, sunshine hours, and wind speed provided an improved prediction of the effect of climate on evapotranspiration (Doorenbos and Pruitt, 1977). The following equation is the result of the analysis of Doorenbos and Pruitt, (1977):

$$ET_r = \{a + b[p(0.46T + 8.13)]\}\left(1 + \frac{Elev}{10000}\right) \tag{1}$$

where

ETr = reference crop ET for grass, mm/d

p = percent of annual sunshine during month on a daily basis

T = mean temperature, °C

a,b = climatic calibration coefficients

Elev = station elevation, m

The term in the brackets $[\bar{p}(0.46T + 8.13)]$ is identical to the original Blaney Criddle method. The contribution of Doorenbos and Pruitt was in the *a* and *b* coefficients which help account for the local climatic conditions. The *a* and *b* climatic calibration coefficients were produced by a step-wise regression analysis on meteorological and lysimeter data from the FAO project. The FAO report gave the following equation for the *a* coefficient and a computerized look-up table for the *b* coefficient (refer to Table 1):

$$a = 0.0043(RH_{\min}) - \left(\frac{n}{N}\right) - 1.41 \tag{2}$$

where

$RH_{min}$ = minimum relative humidity, percent

n/N = ratio of actual to maximum sunshine hours, fraction

Frevert et al. (1983) published a regression equation for b based on the original computerized look-up table produced by Doorenbos and Pruitt (1977). Further simplification of the equation of Frevert et al. (1983) was performed by Cuenca and Jensen (1988) resulting in the following *b* coefficient:

$$\begin{aligned} b = 0.82 - 0.0041(RH_{\min}) + 1.07\left(\frac{n}{N}\right) + 0.066(U_{day}) \\ - 0.006(RH_{\min})\left(\frac{n}{N}\right) - 0.0006(RH_{\min})(U_{day}) \end{aligned} \tag{3}$$

where

$U_{day}$ = daytime windspeed at 2 m height, m/s

TABLE 1: Values of b as function of RHmin, Uday, and n/N

| | RHmin (%) | | | | | | |
|---|---|---|---|---|---|---|---|
| n/N | 0 | 20 | 40 | 60 | 80 | 100 | Uday (m/sec) |
| 0.0 | 0.84 | 0.80 | 0.74 | 0.64 | 0.52 | 0.38 | 0 |
| 0.2 | 1.03 | 0.95 | 0.87 | 0.76 | 0.63 | 0.48 | |
| 0.4 | 1.22 | 1.10 | 1.01 | 0.88 | 0.74 | 0.57 | |
| 0.6 | 1.38 | 1.24 | 1.13 | 0.99 | 0.85 | 0.66 | |
| 0.8 | 1.54 | 1.37 | 1.25 | 1.09 | 0.94 | 0.75 | |
| 1.0 | 1.68 | 1.50 | 1.36 | 1.18 | 1.04 | 0.84 | |
| 0.0 | 0.79 | 0.90 | 0.81 | 0.68 | 0.54 | 0.40 | 2 |
| 0.2 | 1.19 | 1.08 | 0.96 | 0.84 | 0.66 | 0.50 | |
| 0.4 | 1.41 | 1.26 | 1.11 | 0.97 | 0.77 | 0.60 | |
| 0.6 | 1.60 | 1.42 | 1.25 | 1.09 | 0.89 | 0.70 | |
| 0.8 | 1.79 | 1.59 | 1.39 | 1.21 | 1.01 | 0.79 | |
| 1.0 | 1.98 | 1.74 | 1.52 | 1.31 | 1.11 | 0.89 | |
| 0.0 | 1.08 | 0.98 | 0.87 | 0.72 | 0.56 | 0.42 | 4 |
| 0.2 | 1.33 | 1.18 | 1.03 | 0.87 | 0.69 | 0.52 | |
| 0.4 | 1.56 | 1.38 | 1.19 | 1.02 | 0.82 | 0.62 | |
| 0.6 | 1.78 | 1.56 | 1.34 | 1.15 | 0.94 | 0.73 | |
| 0.8 | 2.00 | 1.74 | 1.50 | 1.28 | 1.05 | 0.83 | |
| 1.0 | 2.19 | 1.90 | 1.64 | 1.39 | 1.16 | 0.92 | |
| 0.0 | 1.18 | 1.06 | 0.92 | 0.74 | 0.58 | 0.43 | 6 |
| 0.2 | 1.44 | 1.27 | 1.10 | 0.91 | 0.72 | 0.54 | |
| 0.4 | 1.70 | 1.48 | 1.27 | 1.06 | 0.85 | 0.64 | |
| 0.6 | 1.94 | 1.67 | 1.44 | 1.21 | 0.97 | 0.75 | |
| 0.8 | 2.18 | 1.86 | 1.59 | 1.34 | 1.09 | 0.85 | |
| 1.0 | 2.39 | 2.03 | 1.74 | 1.46 | 1.20 | 0.95 | |
| 0.0 | 1.26 | 1.11 | 0.96 | 0.76 | 0.60 | 0.44 | 8 |
| 0.2 | 1.52 | 1.34 | 1.14 | 0.93 | 0.74 | 0.55 | |
| 0.4 | 1.79 | 1.56 | 1.32 | 1.10 | 0.87 | 0.66 | |
| 0.6 | 2.05 | 1.76 | 1.49 | 1.25 | 1.00 | 0.77 | |
| 0.8 | 2.30 | 1.96 | 1.66 | 1.39 | 1.12 | 0.87 | |
| 1.0 | 2.54 | 2.14 | 1.82 | 1.52 | 1.24 | 0.98 | |
| 0.0 | 1.29 | 1.15 | 0.98 | 0.78 | 0.61 | 0.45 | 10 |
| 0.2 | 1.58 | 1.38 | 1.17 | 0.96 | 0.75 | 0.56 | |
| 0.4 | 1.86 | 1.61 | 1.36 | 1.13 | 0.89 | 0.68 | |
| 0.6 | 2.13 | 1.83 | 1.54 | 1.28 | 1.03 | 0.79 | |
| 0.8 | 2.39 | 2.03 | 1.71 | 1.43 | 1.15 | 0.89 | |
| 1.0 | 2.63 | 2.22 | 1.86 | 1.56 | 1.27 | 1.00 | |

Units for $RH_{min}$ and n/N are indicated in Eq. (2). If the daytime wind speed is measured at a height other than 2 meters, application of the log-wind law is used to adjust the measured height to 2 meters. The log-wing law is given in the following equation:

$$U_{2m} = U_z \left( \frac{2.0}{z} \right)^{0.2} \tag{4}$$

where

$U_{2m}$ = equivalent wind speed at 2 m

$U_z$ = wind speed measured at height z

z = height of measurement, m

### 2.2.1.2 Additional Adjustments to FAO-Modified BC

Additional adjustments to the FAO-modified Blaney Criddle were derived by Allen and Brockway (1982) at the United States Department of Agriculture (USDA) lysimeter site located at the Snake River Water Conservation Laboratory in Kimberly, Idaho. The lysimeter at Kimberly is maintained in alfalfa. Only the most important aspects of the adjustments are discussed. Complete details of the work are found in the publication by Allen and Brockway (1982).

Two reasons existed for the additional calibrations. By analyzing the lysimeter data from Kimberly, Allen and Brockway (1982) demonstrated that the FAO-modified Blaney Criddle method overpredicted crop water use for the grass reference during the middle of the growing season. Secondly, the standard deviations of evapotranspiration using the estimates from the FAO-modified Blaney Criddle were less than those measured from the lysimeter. Cuenca and Amegee (1987) noted that this second point is important if the predicted evapotranspiration and crop water use pattern is to be applied in probability analysis for irrigation or water resource system design.

The work by Allen and Brockway produced calibrations to adjust the crop water use and standard deviation of evapotranspiration. Table 2 shows the computed monthly adjustment ratios for ETr and standard deviations of evapotranspiration. For the climate conditions at Kimberly, the FAO alfalfa to grass coefficient, i.e. $ET_{alf}/ET_r$, should be 1.15 (Doorenbos and Pruitt, 1977). For the middle of the growing season, July through August, Table 2 indicates that the FAO-modified BC method overpredicted grass ETr.

TABLE 2: Monthly Adjustment Ratios for Reference Evapotranspiration and Standard Deviations of Evapotranspiration[a]

| MONTH | $ET_{alf}/ET_r$ | $\sigma_{meas}/\sigma_{calc}$ |
|---|---|---|
| April | 1.21 | 1.70 |
| May | 1.14 | 1.64 |
| June | 1.07 | 2.70 |
| July | 1.01 | 2.22 |
| August | 1.00 | 2.13 |
| September | 1.08 | 1.61 |
| October | 1.22 | 1.35 |

[a] Taken from Allen and Brockway, 1982.

The correction equation developed by Allen and Brockway for the adjusted monthly grass ETr follows:

$$ET_{r-adj} = ET_r(ET_{alf}/ET_r)/1.15 \qquad (5)$$

where

$ET_{r-adj}$ = adjusted ETr for grass

ETr = reference evapotranspiration calculated from Eq. (2)

$ET_{alf}/ET_r$ = adjustment ratio from Table 2

The analysis conducted for this thesis did not involve probability analysis of evapotranspiration for irrigation requirements, therefore monthly adjustment ratios for standard deviations of ET were not used. Calibration for the standard deviation could be accomplished by applying eq. (6). For more information on this calibration, refer to Allen and Brockway (1982) and Allen and Wright (1983).

$$\sigma_{adj} = \sigma_{calc}(\sigma_{meas}/\sigma_{calc}) \tag{6}$$

where

$\sigma_{adj}$ = adjusted standard deviation for ET

$\sigma_{calc}$ = calculated standard deviation for ET

$\sigma_{meas}/\sigma_{calc}$ = adjustment ratio from Table 2

Allen and Brockway (1982) developed an additional calibration to adjust for site aridity. Stations located in completely arid environments tend to have higher temperatures than adjacent stations exposed to the same meteorological conditions but in irrigated environments (Allen et al., 1983). Reference evapotranspiration is supposed to be representative, by definition, of moist, non-arid sites. An equation for an aridity rating was therefore derived to adjust temperature data collected from stations with arid surroundings. The aridity rating is given by the following equation:

$$AR = 0.4(Site\,AR) + 0.5(Area\,AR) + 0.1(Regional\,AR) \tag{7}$$

where

AR = cumulative aridity rating

Site AR = aridity of environment within a 50-m radius of sensor, %

Area AR = aridity of area within a 1.5-km radius of sensor, %

Regional AR = aridity of region within a 50-km radius of sensor, %

The range of the individual aridity ratings is from zero to 100 percent. Zero percent aridity rating represents a completely irrigated environment. Conversely, a 100 percent rating represents a completely arid environment. Application of the aridity factor is discussed in the Methods and Data Selection Section.

### 2.2.2 REGIONAL EVAPOTRANSPIRATION ESTIMATING METHODS

The scientific community has become increasingly more concerned with the scale in which environmental systems are being examined. Both in the development of water resources for agricultural or other uses and hydrologic modeling, it is required to analyze ET on a regional scale. There are a number of articles describing ET estimates at a local scale and comparisons between the various local ET estimating methods (Doorenbos and Pruitt, 1977; Jensen, 1974; Burman et al., 1983; Allen and Brockway, 1983). However, until recently limited attention has been given to estimating regional evapotranspiration. The work of Morton (1969, 1979, 1978, 1983) concentrated on the analysis of regional ET. Other work was done by Cuenca et al.(1981), Brutseart and Stricker (1979), Seguin (1973, 1975), and Amegee (1985).

Seguin et al. (1982) recommended two main criteria in developing methods for estimating regional ET. The first criteria is to ensure the estimates of ET are representative of the whole surface including the heterogeneity of elementary surfaces making up the regional scale. The second criterion stipulates that the procedure or technique for estimating regional ET must be simple enough to be used for practical purposes given the common network of climatic stations.

The typical approach is to reduce the region into small homogenous units for which local methods may apply, compute the local ET estimate over each homogenous surface, and then take a weighted average of these estimates to represent the region. Other methods have been examined for estimating regional ETr. Brutseart and Mawdsley (1976) extended the Penman aerodynamic method to the planetary boundary layer in estimating regional ET. Rouse and Stewart (1972) described an approach called the equilibrium evaporative approach in which regional ET was approximated by the global radiation term of Penman's equation. Davies and Allen (1973) proposed an extension of the Priestly-Taylor formulation by a parameter dependent on soil moisture conditions.

Recent developments in the technology and techniques of remote sensing have suggested the possibility using remote sensing as a useful tool in improving local and regional evapotranspiration estimates. Much of the technology for collecting the weather and surface parameters needed for ET estimates exists, however the main problem is incorporating remote sensing data with ground-based measurements. Although some resulting formulas offer promising results, their validity has not been adequately verified with respect to soil moisture and cloudy sky conditions to allow operational estimates of regional ETr (Schmugge, 1978; Bernard et al., 1981).

An acceptable method currently practiced in some western states applies local mean monthly estimated ETr to produce contour maps of these estimates. Maps of the entire state of California for each month of the year were recently published. ETr values for approximately 400 sites within California were used to develop detailed isolines for the state (Pruitt et al., 1987). Currently, similar work is being completed in Oregon to develop isolines of mean monthly estimated ETr. In Oregon, the FAO-modified Blaney Criddle method with USDA adjustments was used to estimate ETr at 245 locations. A contouring package, SURFER, was applied to produce the maps of the isolines of ETr.

Amegee (1985) applied geostatistics to regional evapotranspiration. This analysis produced a grid of estimated ETr based on the spatial variability of this parameter as described using geostatistics. The gridded estimates of ETr provided information to develop detailed isolines. Although Amegee (1985) offered promising results, more research was required before geostatistics could be widely used in estimating regional ETr.

## 2.3 FUNDAMENTAL CONCEPTS OF GEOSTATISTICS

### 2.3.1 OVERVIEW

At the beginning of the 1960's, G. Matheron (1962-63) built his theory of regionalized variables and proposed a method of estimation called 'kriging'. This method was named after D.G. Krige, who had done some empirical work in South Africa to estimate ore reserve in gold mines. The essence of this theory is that a regionalized variable can be characterized by the correlation between neighboring measurements (Journel and Hujbregts, 1978). This spatial correlation suggests that a value or a sample of some variable is related or correlated in some manner to the value at spatial locations some distance away. This correlation is used to construct a model characteristic of the spatial variation of the desired parameter. This model is used to estimate the parameter at locations where no measurements are available and calculate the error associated with the estimation. Much of the application of regionalized variable analysis was limited to the field of mining. During the last few years, this method has been extended to a large variety of fields including geophysics, meteorology, ecology, geography and oceangraphy (Henly, 1981). Delhomme (1978) stated that it has proven to be particularly well suited to the problems encountered in hydrosciences. Clark (1979) also emphasized that this estimation technique can be used wherever a continuous measurement is made of a variable at a particular location in space or time i.e. where a sample value is expected to be affected by its position and its relationship with its neighbors.

Geostatistics refers to the application of the theory of regionalized variables to practical problems. Geostatistics has been successfully applied to a number of hydrologic variables because the variation of hydrologic parameters generally has a definable structure (Amegee and Cuenca, 1987). There are two tools applied in geostatistics. The first tool, the variogram, attempts to define the functional form of spatial variation of the variable. The second tool, the kriging systems of equations, applies this defined spatial variation in interpolating the variable to locations where no data exist. The purpose of the following sections is to present the two main geostatistical tools. The material has been greatly simplified in order to provide at least an initial understanding of the concepts behind geostatistics. A complete derivation of the major principles of geostatistics using evapotranspiration as the regionalized variable can be found in Cuenca and Amegee (1987). For a complete introduction into geostatistics, the following references are recommended: Clark (1979), David (1977), and Journel and Hujbregts (1978).

### 2.3.2 SEMIVARIANCE FUNCTION

The semivariance function attempts to define the variation of the variable, such as evapotranspiration, with respect to distance between known data points. One way to compare two values $ET(x)$ and $ET(x+h)$, separated by distance $h$, is to compute their differences. Typically, one is more interested in comparing all the values separated by a given distance $h$, $n(h)$. Thus computing the average of the quantity $[ET(x)\text{-}ET(x+h)]$ would be more useful. This computation can be written as follows:

$$D(h)=\frac{1}{n(h)}\sum_{i=1}^{n(h)}[ET(x_i)-ET(x+h)_i] \qquad (8)$$

where

ET(x) = evapotranspiration measured at point x

ET(x + h) = evapotranspiration measured at point x + h

$D(h)$ is the estimate of the mathematical expectation of the difference $[ET(x)\text{-}ET(x+h)]$. A plot of $D(h)$ for different distances $h$ is termed the drift.

The drift, $D(h)$, can be positive, negative, or zero. But in geostatistics the interest is in the absolute value of the changes as a function of distance. This can be accomplished by computing means of the absolute values of the changes which can be quite time consuming. Another method is to compute the mathematical expectation of the squared difference of *[ET(x)-ET(x+h)]* which is defined as:

$$2\gamma(h) = E\{[ET(x) - ET(x+h)]^2\} \tag{9}$$

$2\,\gamma(h)$ is termed variance function. The semivariance evaluated at distance *h* between two measurements is defined as one half of the expected value of the squared difference of *ET(x)* and *ET(x+h)*. In equation form this becomes

$$\gamma(h) = \frac{1}{2}E\{[ET(x) - ET(x+h)]^2\} \tag{10}$$

where

$\gamma(h)$= semivariance for distance h

Converting the expected value notation into computational form, equation (10) becomes

$$\gamma(h) = \frac{1}{(2N(h))}\sum_{i=1}^{N(h)}[ET(x_i) - ET(x+h)_i]^2 \tag{11}$$

where

N(h) = number of data pairs of measured evapotranspiration separated by distance h

#### 2.3.2.1 Assumptions

A major premise of geostatistics is the ability to define the variation of a random variable as a function of distance. The magnitude of the function characterizing the variation of the random variable may be different from one location to another. However, the mathematical expression of the underlying variability function should be stable over the area of interest. This property is called stationarity. In geostatistics, four possible assumptions can be made.

### First Order Stationarity

The most restrictve assumption is first order stationarity which is met when the mean difference between observations is equal to zero. First order stationarity indicates there is no trend (Clark, 1979) and the variable is homogenous throughout the area of interest. An indicator of the validity of first order stationarity is the drift, $D(h)$. If the difference $D(h)$ is zero for all values of h over the region considered, the regionalized random variable is said to have first order stationarity (i.e. there is no drift) (Amegee, 1985). The magnitude of deviations of the drift from zero indicates how much the region is heterogeneous with respect to the variable. If there is a trend to the value of the drift as a function of distance, the mean cannot be assumed constant over the domain of analysis (Cuenca and Amegee, 1987). Methods have been developed to deal with the case of a mean which is not stationary but which varies in a regular manner over the domain (David, 1977; Matheron, 1971).

### Second Order Stationarity

This assumption is also termed weak-stationarity and is seldom found in natural phenomena. Two conditions are required in this assumption:

1. The expected value of the regionalized variable $ET(x)$ is the same over the field of interest;

2. The spatial covariance of the regionalized variable $ET(x)$ is the same over the field of interest.

The first condition suggests that the expected value of the variable is equal to the mean of the data measured over the region of interest. This condition can be written as follows:

$$E[ET(x)] = m \tag{12}$$

The second condition of second order stationarity implies that for each pair of random variables, the covariance exists and depends on the separation *h*. The covariance is defined as the expected value of the product of deviations of two observations from the mean. In its computational form, the covariance is written as follows:

$$C[ET(x),ET(x+h)] = \frac{1}{N(h)} \sum_{i=1}^{N(h)} [ET(x)_i - m][ET(x+h)_i - m] \tag{13}$$

where $N(h)$ is as previously defined.

The stationarity of the covariance implies stationarity of the variance (Amegee, 1985). Therefore, as the distance *h* is reduced to zero, the covariance becomes the variance as shown below:

$$\sigma^2[ET(x)] = \frac{1}{(n-1)} \sum_{x=1}^{n} [ET(x)_i - m]^2 \tag{14}$$

where *n* is as previously defined. Under the hypothesis of first and second order stationarity, there is a constant and finite mean and the covariance and variance exist for the variable of interest. In this case, the semivariance equals the variance minus the covariance, which is given by the following equation (Cuenca and Amegee, 1987):

$$\gamma(h) = \sigma^2[ET(x)] - C[ET(x),ET(x+h)] \tag{15}$$

Second order stationarity suggests there is a known variance and covariance independent of *x*. According to Journel and Huijbregts (1978), there are several natural phenomena and random functions which have an infinite capacity for dispersion, i.e. neither have a known variance or covariance, but for which a variogram can be defined. Second order stationarity does not apply if a variance and covariance cannot be defined, as in the case of trends. In this case, a weaker form of stationarity called the intrinsic hypothesis must be assumed.

**Intrinsic Hypothesis**

For the intrinsic hypothesis, the assumption is that the random variable is not required to have known variance, however the change in the variable should have a definable variance. The intrinsic hypothesis requires that for all distances of $h$, the variance of the increments of the function, $ET(x)\text{-}ET(x+h)$, rather than the function itself, be finite, equal, and independent of postion over the field of interest. The semivariance is actually equal to one-half the variance of $ET(x)\text{-}ET(x+h)$:

$$\gamma(h)=\frac{1}{2}\sigma^2[ET(x)-ET(x+h)] \tag{16}$$

The semivariance is said to define the spatial structure of the variation of the parameter of interest rather than the spatial structure of the parameter itself (Cuenca and Amegee, 1987).

**Hypothesis of Universal Kriging**

This last hypothesis is less restrictive than the previous one and assumes the variance of the increments, $ET(x)\text{-}ET(x+h)$, has some properties of stationarity within a vicinity of restricted size and that the expectation, $E[ET(x)]$, which is no longer stationary, varies in a regular manner in such a vicinity (David, 1977). For this hypothesis, the drift term, $D(h)$, is not equal to zero, but represents some trend which can be statistically derived by a linear regression technique. This linear regression model of the drift is used in the kriging analysis of the data to account for the drift. More details on universal kriging can be found in David (1977). According to Journel and Hujbregts (1978), quasi-stationarity or the hypothesis of universal kriging is a compromise between data availability and strict stationarity because it is always possible by reducing the vicinity to produce a zone so small that the stationarity is verified. However, Amegee (1985) noted this reduction would not always be possible because of economical constraints related to station density for data collection.

### 2.3.2.2 Properties

A plot representing all the possible values of the semivariance function, $\gamma(h)$, as a function of $h$ is termed a sample variogram. To compute a variogram, one uses Eq. 10 for all possible distances $h$ which is sometimes called the lag. Through a graphical representation of $\gamma(h)$ versus lag $h$, a curve can be fitted to the cloud of points representing the pairs $\{h, \gamma(h)\}$. This curve is referred to as the model variogram. Certain properties of the variogram are discussed in this section . First, the ideal model of the variogram will be explained followed by four common models applied in variogram analysis.

**Ideal Model**

A representation of an ideal variogram is depicted graphically in Figure 2. An ideal variogram is expected to maintain certain properties. As shown in the figure, the semivariance is a postitive quantity going to zero as the distance $h$ goes to zero. Information on the spatial correlation of the variable will be limited to distances greater than the smallest separation between a pair of samples (Cooper and Istok, 1987). Cases in which the range of influence is less than the smallest separation will display a discontinuity at the origin. Sampling and analysis errors also contribute to this discontinuity which is termed the nugget, $C_o$.

Also seen in Figure 2, the variogram ideally approaches the variance asymptotically until, at a distance designated the range, it is equal to the variance within some error criteria, $\Delta$. This maximum value is termed , $C_1$. In the presence of a nugget effect, $C_1$ is equal to $C_o + C$, where the $C$ term is called the sill value. Conversely, when $C_o$ is zero, the sill value is equal to the variance. The range, $a$, represents the distance beyond which no relationship of the spatial structure for the variable exists.

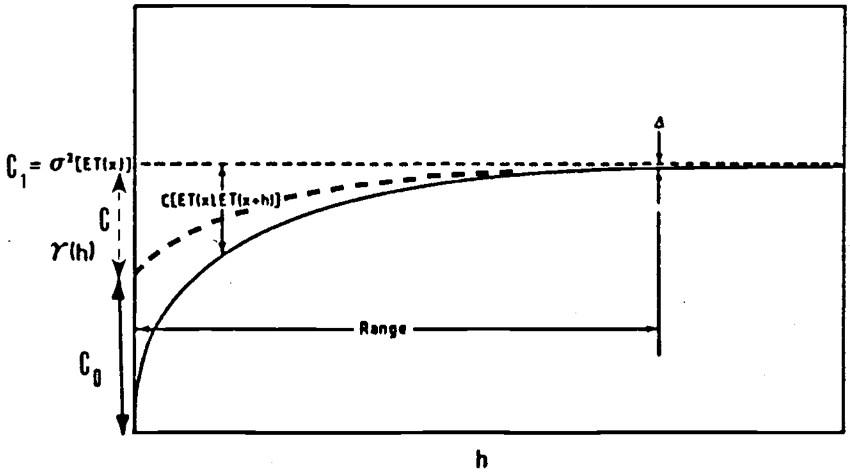



Figure 2: Ideal Variogram

## Four Common Models

Amegee (1985) commented that no matter how well an model variogram fits the points which represent the computed $\gamma(h)$, the model variogram cannot perfectly describe the variability of a natural phenomenon in a region. A variogram can be modeled by any mathematical function as long as it is conditional positive-definite (increasing or constant with increasing h and nonnegative) (Olea, 1975). However, in practice only four common functions are typically observed and used in geostatistics:

(1) Linear model:

$$\gamma(h) = C_o + b * h \qquad 0 \le h \le a$$

$$\gamma(h) = C_o + C \qquad h > a \tag{17}$$

where b is the slope

(2) Spherical model:

The spherical model is the most commonly used function in geostatistics. David (1977) noted that it has been possible to estimate a hundred ore deposits with only the spherical and exponential model and the tendency is to use only the spherical model. The mathematical form of this model is written as follows:

$$\gamma(h) = C_o + C\left[\frac{3}{2}\left(\frac{h}{a}\right) - \frac{1}{2}\left(\frac{h}{a}\right)^3\right] \qquad 0 \leq h \leq a$$

$$\gamma(h) = C_o + C \qquad h > a \tag{18}$$

where

Co = nugget effect

$C_1$ = variance of the random variable

a = range of influence of the semivariance function

(3) Exponential model:

$$\gamma(h) = C_o + C\left[1 - \exp\left(-\left(\frac{h}{a}\right)\right)\right] \qquad 0 \leq h \leq a$$

$$\gamma(h) = C_o + C \qquad h > a \tag{19}$$

(4) Gaussian model:

$$\gamma(h) = C_o + C\left[1 - \exp\left(-3\frac{h^2}{a^2}\right)\right] \tag{20}$$

**Istropic and Anistropic**

A variogram model can be isotropic or anisotropic. If all the variograms represent identical models regardless of the direction of *h*, the variogram is termed isotropic. Therefore, the spatial correlation depends only on the distance of *h* and not the direction.

It follows that when the variogram is a function of the direction of *h*, the variogram is anisotropic. When the variogram is anisotropic, a variogram must be determined for each direction of isotropic. Two types of anisotropy have been identified in geostatistics, geometric and zonal (Amegee, 1985).

### 2.3.3 KRIGING

Kriging is the interpolation technique of geostatistics which makes optimal and unbiased estimates of regionalized variables at unknown locations using the structural properties of the variogram and known data values. There are two types of kriging : simple, ordinary, and universal. Simple and ordinary kriging are applied for the case of second order stationarity and the intrinsic hypothesis. Simple kriging assumes that local means are relatively constant and equal to the mean of the data. Ordinary kriging assumes the local means are not closely related to the mean of the data. In the case of a drift or nonstationarity, universal kriging is the technique applied. These types of kriging have two forms of estimation, point or block. Point estimation refers to estimation of the variable, such as $ET(x)$, at a single location. Block estimation is performed by applying the interpolation technique of the mean value of $ET(x)$ over a block portion of the region of interest.

The following sections presents the governing equations, constraints, and kriging system of equations for the case of ordinary point kriging. Details on universal kriging can be found in David (1977). As mentioned before, the following material has been greatly simplified. A complete derivation of the kriging system of equations with evapotranspiration as the regionalized variable can be found in Cuenca and Amegee (1987).

### 2.3.3.1 Governing Equation

The governing equation for estimating a variable at an unmeasured point using kriging is based on a linear condition. The kriging estimate for a variable at an unknown location is represented by a linear combination of measured data at surrounding locations, each measured value receiving different weights. Therefore, the closer a neighboring point is to the desired point, the more heavily its value is weighted when the unknown values are estimated. The governing equation can be written as:

$$ET^{*}(x_p) = \lambda_1 ET(x_1) + \lambda_2 ET(x_2) + \lambda_3 ET(x_3) + \cdots + \lambda_n ET(x_n) \tag{21}$$

where

$ET^{*}(x_p)$ = kriging estimate of evapotranspiration at point $x_p$

$ET(x_i)$ = measured value of evapotranspiration at point $x_i$

$\lambda_i$ = weight assigned to each measured value

To minimize computing costs, in practice n is limited to only the number which lie closest to the point at which $ET^{*}(xp)$ is being estimated (Cuenca and Amegee, 1987). The assigned weights applied to each measured value is determined using two constraints required to derive the kriging system of equations coupled with the variogram.

### 2.3.3.2 Constraints

The two conditions used to compute the weights are:

1. Unbiasedness: The mean of the kriging estimates is equal to the mean of the observed data.

2. Best criterion: The variance of the error between the kriging estimate and the true value is minimized.

The unbiased condition may be expressed as

$$E[ET^{*}(x)] = E[ET(x)] = m \tag{22}$$

$$E[ET^{*}(x)] = \frac{1}{n}\sum_{i=1}^{n}\lambda_i ET(x_i) = m\sum_{i=1}^{n}\lambda_i \tag{23}$$

The result of applying an unbiased condition is that the sum of the individual weights must be equal to 1. This result is obtained by combining Eqs. (22) and (23):

$$\sum_{i=1}^{n}\lambda_i = 1 \tag{24}$$

The second condition, the best criterion, states that the variance of the estimation error be minimized. This condition is written as follows:

$$\sigma^2[\epsilon_p] = \sigma^2[ET(x_p)] - 2\sum_{i=1}^{n}\lambda_i C[ET(x_p), ET(x_i)] +$$

$$\sum_{i=1}^{n}\sum_{j=1}^{n}\lambda_i\lambda_j C[ET(x_i), ET(x_j)] \tag{25}$$

Eq. (25) must be solved for those weights $\lambda_i$ which minimize the estimation variance under the constraint that the sum of the weights be equal to 1.

### 2.3.3.3 Kriging System of Equations

The kriging system of equations results from applying the previous conditions to Eq. (25) in an attempt to solve for the weights. To minimize Eq. (25), it is necessary to take the derivative with respect to the weights. In doing so, one realizes the need to introduce a Lagrangian multiplier, $-2\mu$, to rectify the situation of having n + 1 equations for n unknowns (Cuenca and Amegee, 1987). The final result is the following kriging system of equations:

$$\lambda_1\gamma(h_{11}) + \lambda_2\gamma(h_{12}) + \ldots + \lambda_n\gamma(h_{1n}) + \mu = \gamma(h_{1p})$$
$$\lambda_1\gamma(h_{21}) + \lambda_2\gamma(h_{22}) + \ldots + \lambda_n\gamma(h_{2n}) + \mu = \gamma(h_{2p})$$
$$\vdots$$
$$\lambda_1\gamma(h_{n1}) + \lambda_2\gamma(h_{n2}) + \ldots + \lambda_n\gamma(h_{nn}) + \mu = \gamma(h_{np})$$
$$\lambda_1 + \lambda_2 + \ldots + \lambda_n + 0 = 1.0 \qquad (26)$$

The $\gamma(h)$ in Eq. (26) are determined from the variogram thus allowing the unknown weights $\lambda_i$ to be solved. The resulting, $\lambda_i$, are used in Eq. (21) with measured values of evapotranspiration to produce the kriging estimate of evapotranspiration at the unmeasured location, *ET*(xp)*. As concluded by Cuenca and Amegee (1987), the kriging system of equations is said to result in the best-linear-unbiased estimate.

# 3 METHODS AND DATA SELECTION

The state of Oregon was selected as the geographic base. A project conducted by the Water Resources Engineering Team of the Department of Agricultural Engineering at Oregon State University was recently completed to produce revised estimates for consumptive use and net irrigation requirements for Oregon. Much of the methods and data analysis from this project were incorporated into this thesis. This chapter describes the available weather data, choice of the ETr estimating method, determination of the five climatic regions, and geostatistical programs applied in analyzing the ETr data.

## 3.1 CHOICE OF EVAPOTRANSPIRATION METHOD

The FAO-Modified Blaney Criddle Method was chosen as the estimating method for the revision work and this thesis. As mentioned in the Literature Review, the studies performed in Washington, Idaho, and Oregon suggested that this would be the best temperature-based method to use. The decision to use this empirical method was based upon known availability of temperature data throughout Oregon. The data required by the FAO-modified Blaney Criddle are broken into primary weather parameters and secondary weather parameters. These two types of data are discussed in the following section.

A computer program, CROPMIR, was written in QuickBASIC to computed the evapotranspiration estimate along with the net irrigation requirements of specific crops during the revision project performed by the Water Resources Engineering Team. The subprogram BLACRI calculated the ETr. IT was used in this project to estimate ETr at 180 locations given the following input data: monthly average maximum and minimum daily temperatures (Tmax and Tmin), monthly minimum relative humidity (RHmin), ratio of actual to maximum possible sunshine hours (n/N), daytime average windspeed at 2 m height (Uday), latitude, longitude, and elevation. The output of this subprogram was ETr estimates for each month and location where weather station data were available. For this thesis, ETr estimates during 1985, 1986, and 1987 for May through September at 180 weather stations were calculated and used in the geostatistical analysis. A listing of the subprogram BLACRI is in Appendix C.

## 3.2 AVAILABLE WEATHER DATA

### 3.2.1 PRIMARY WEATHER DATA

The primary weather data consisted of monthly averages of daily maximum and minimum air temperature. Kelly Redmond, State Climatologist, provided the monthly averages of daily maximum and minimum air temperature recorded by the various weather stations throughout the state of Oregon. 180 primary stations had the required air temperature data for the given months in the three years studied. Appendix A gives the listing of the primary weather stations chosen for this work. Figure 3 shows the distribution of these stations throughout the state.

### 3.2.2 SECONDARY WEATHER DATA

The secondary weather data required to estimate ETr by the FAO-modified Blaney Criddle method include long-term monthly averages of minimum relative humidity, ratio of actual to maximum possible sunshine hours, and daytime average wind speed at 2 m height. These data were available from a number of different sources for a limited number of weather stations. Figures 4, 5, and 6 show the location of the weather stations providing the secondary weather data. A detailed examination of the secondary data sources for each station was made. The source chosen was based on the length of recorded data and ease of obtaining and processing the information.

WEATHER STATIONS FOR THE STATE OF OREGON

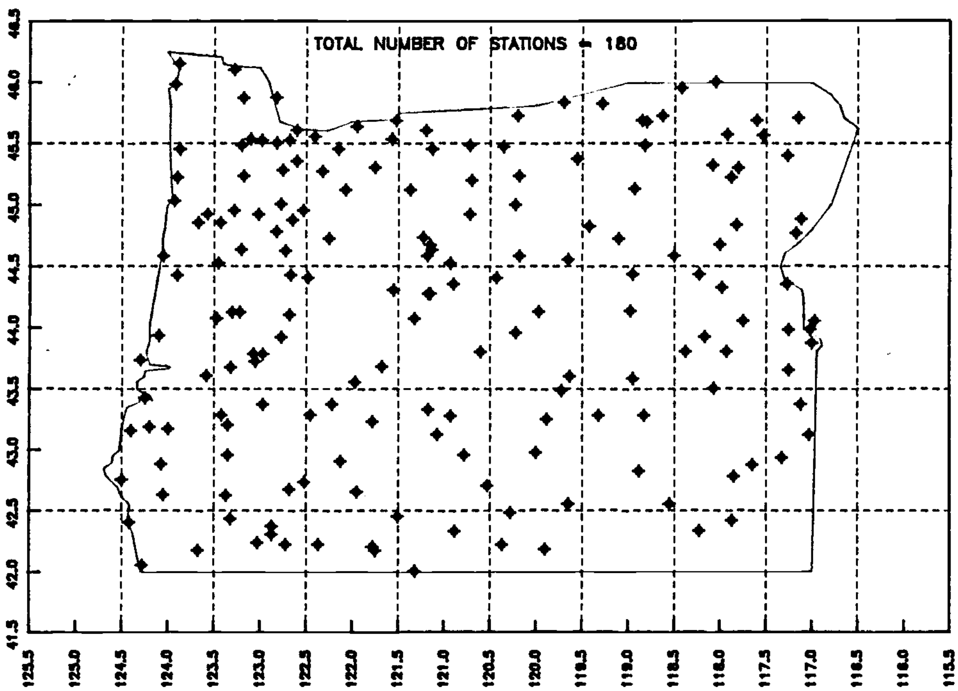



Figure 3: Primary Weather Stations for Oregon

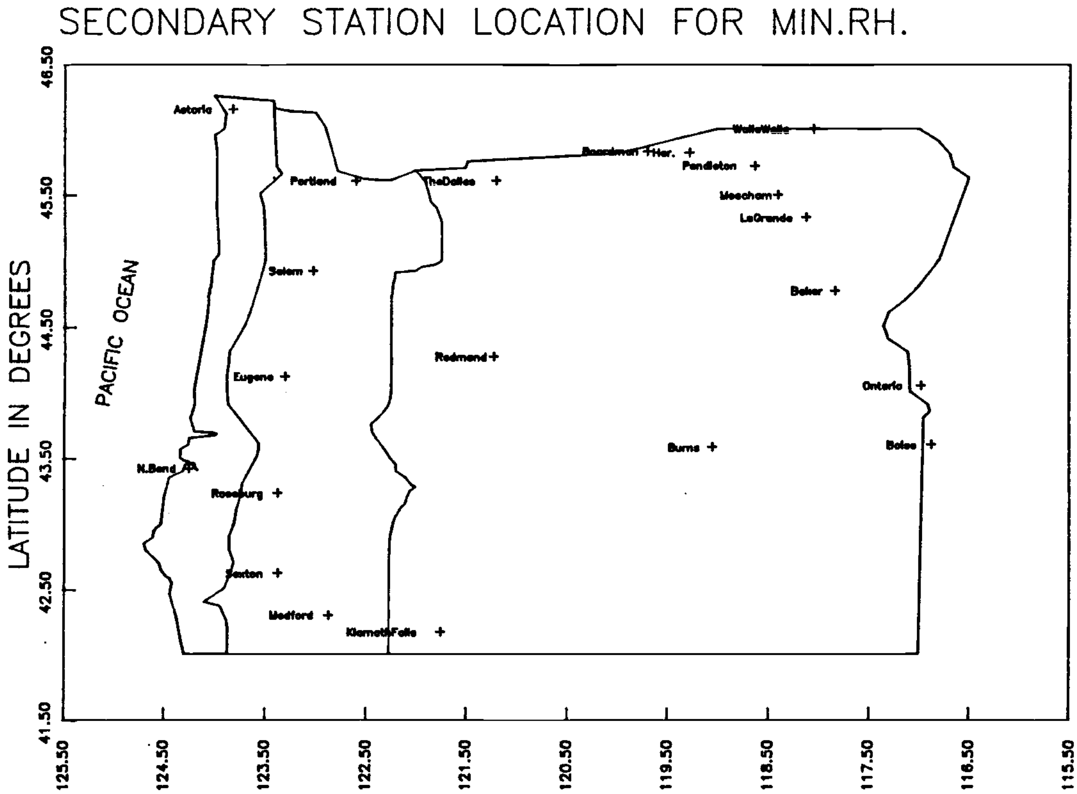



Figure 4: Location of Weather Stations giving RHmin

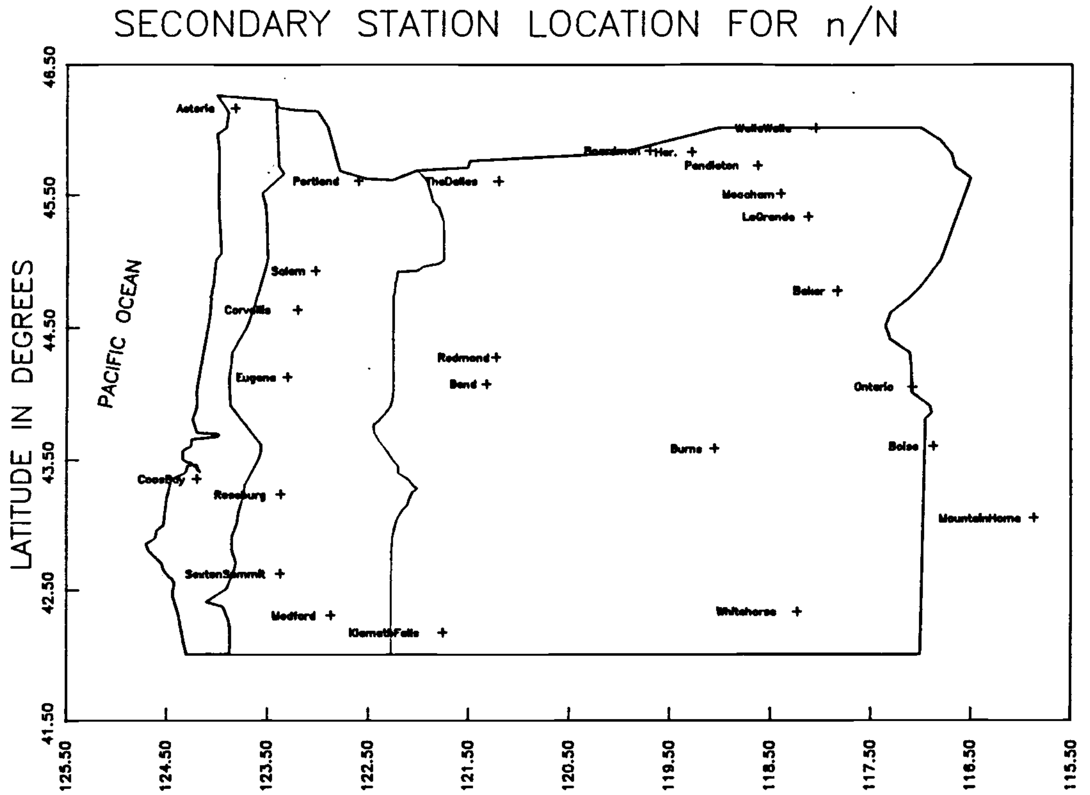



Figure 5: Location of Weather Stations giving n/N

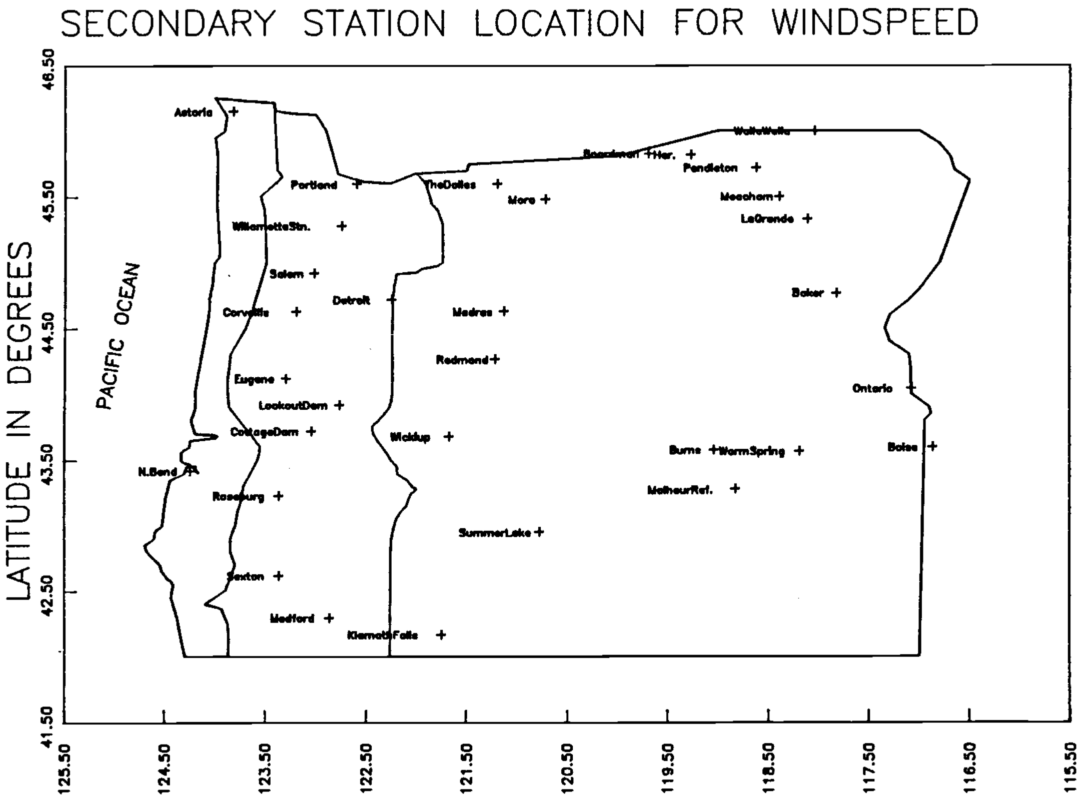



Figure 6: Location of Weather Stations giving windspeed

For the minimum relative humidity, 21 weather stations were identified. Appendix B lists the stations used, the different sources giving information on minimum relative humidity at each station, and the data source used in the final analysis. Stations providing dewpoint temperature were employed with an empirical relationship between dewpoint temperature and air temperature to estimate minimum relative humidity. The following equation represents that relationship (Cuenca, 1989):

$$RH_{min} = 100\frac{\{112 - 0.1(Tmax) + Tdp\}}{\{110 + 0.9(Tmax)\}} \tag{27}$$

where

Tmax = maximum temperature, °C

Tdp = dewpoint temperature, °C

The ratio of actual to maximum possible sunshine hours (n/N) was available at 25 weather stations. The stations and the associated sources giving information on n/N are listed in Appendix B including the data source used in the analysis. Stations with cloud cover information were utilized by applying the relationship described in FAO 24 (Doorenbos and Pruitt, 1977) to get n/N. Below is the relationship between cloudiness and the n/N ratio.

| cloudiness(tenths) | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| n/N ratio | .95 | .85 | .8 | .75 | .65 | .55 | .5 | .4 | .3 | .15 | |

Stations with incoming shortwave solar radiation information employed the following equation to estimate n/N:

$$n/N = [Rs/(0.5)Ra] - 0.5 \qquad (28)$$

where

Rs = incoming shortwave solar radiation, mm/d

Ra = atmospheric solar radiation, mm/d (Table 2, Doorenbos and Pruitt, 1977, FAO 24, pg. 9 and 12)

Daytime windspeed at 2m height was available at 32 stations. Appendix B provides a list of the stations used, the different sources giving information on daytime windspeed at each station, and the data source used in the final analysis. Some of the stations had to be adjusted to 2m height using Eq.(4) as discussed in the Literature Review section.

Once RHmin, n/N, and windspeed were determined at the 21, 25, and 32 weather stations, respectively, interpolation of these values to the primary station locations was required. For this procedure, Oregon was divided in three zones: 1) coast, 2) Willamette and Southwestern Valleys, and 3) east of the Cascades. Stations with secondary data in each of these zones were used to interpolate the secondary parameters to the primary weather stations in the same zones. A computer program, INTER.BAS, was written to perform the interpolations. This program employed an inverse distance technique such that the influence of a data point declines with a weighting power of distance. In this case, an inverse square distance method was chosen. A search radius of 192 km (120 miles) was used to ensure that at least every primary location had one secondary location to interpolate the secondary values.

### 3.2.3 ARIDITY FACTORS

To perform the USDA adjustments discussed in the Literature Review, information on the site, area, and region of the weather station was required. Descriptive information of the station location and its surroundings was obtained through a personal visit with Clint Jensen (National Weather Service, Portland, Oregon). Aridity factors were subjectively made for the site, area, and region based on the information provided by Mr. Jensen. Cumulative aridity was computed using equation (7) described in the Literature Review section. The cumulative aridity rates provide an adjustment to the air temperature data in arid surroundings. A listing of the site, area, region, and cumulative aridity rates for each station are in Appendix A.

## 3.3 CLIMATIC REGIONS FOR ANALYSIS

The state of Oregon was divided into five climatic regions based on topographic features and local meteorological conditions: 1) Coastal, 2) North intermountain valley, 3) South intermountain valley, 4) North high plateau, and 5) South high plateau (Amegee, 1985). Figure 7 shows the five climatic regions for the state of Oregon. Looking at a topographic map of Oregon, the most noticeable features are two north south mountain ranges, the Coastal and Cascade ranges, the valley resting between the two mountain ranges, and the high plateau and highlands east of the Cascades. West of the Cascades, the climate is humid with an average annual precipitation of approximately 1000 millimeters (40 inches) in the intermountain valleys. East of the Cascades, the climate is semi-arid to arid with an annual precipitation of approximately 250 millimeters (10 inches) or less.

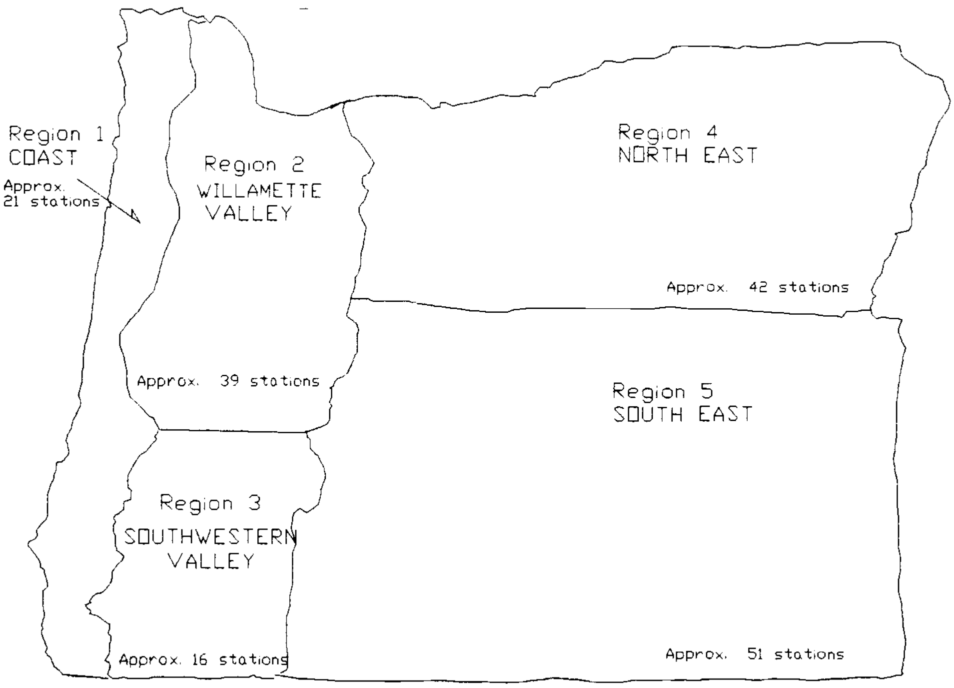



Figure 7: Division of Climatic Regions for the State of Oregon

The five climatic regions were the basis for the regions used in the geostatistical analysis. The 180 weather stations were separated into their respective regions. Appendix A includes a listing of the name, location, and region of each weather station.

To reveal the variability of evapotranspiration between regions, the average ETr in the regions for each month were plotted in Figure 8. The plot indicates distinct differences in estimates of evapotranspiration between certain regions.

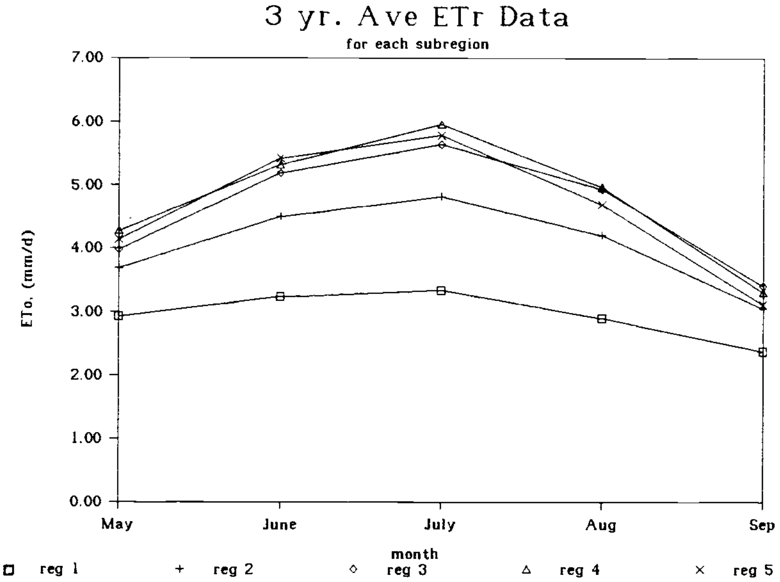



Figure 8: ETr Plot for Each Climatic Region

## 3.4 COMPUTER PROGRAMS FOR GEOSTATISTICAL ANALYSIS

A search for available geostatistical application programs was made at the start of this work. It was desired to utilize a package which provided variogram analysis, cross validation, kriging, and contour mapping routines in a user friendly environment.

The software chosen for this work was developed by the Environmental Protection Agency (EPA), in cooperation with the Applied Earth Sciences Department at Stanford University and the Computer Sciences Corporation. Geo-EAS (Geostatistical Environmental Assessment Software) is a collection of interactive software tools for performing two-dimensional geostatistical analyses of spatially distributed data. The program is menu driven and provides data file management, data transformations, univariate statistics, variogram analysis, cross validation, kriging, contour mapping, post plots, and line/scatter graphs.

The program VARIO in Geo-EAS was used to compute the semivariance functions and to model the sample variograms. The cross validation procedure was performed by the XVALID program in Geo-EAS. The kriging program KRIGE in Geo-EAS was used to estimate regional ETr at points on a grid representative of the individual regions. The contouring package used was SURFER from Golden Software. This contouring package proved to be more useful than the contouring program provided in Geo-EAS.

# 4 PROCEDURE FOR GEOSTATISTICAL ANALYSIS

The geostatistical analysis involved data preparation, variogram modeling, cross validation, kriging and mapping the estimates of ETr. An outline of each step of the procedure was discussed in the first section of this chapter. The sections following indicate details of data preparation, variogram modeling, cross validation, kriging and mapping of the ETr estimates.

## 4.1 PROCEDURE FOR ANALYSIS

The procedure applied consisted of the following steps:

1. Inspect the data using STAT1 from Geo-EAS. Each data set was checked for outliers and statistical information such as the mean, standard deviation, and sample variance was calculated. The outliers in the data were determined and removed. This procedure is discussed in detail in Section 4.2.

2. Following verification of the data set, the semivariance functions were calculated and plotted, using VARIO, to visualize the sample variogram. A model variogram was fitted to the data. The details of the variogram modeling are discussed in Section 4.3.

3. The model variogram was cross validated using XVALID. The cross validation results were checked with the criteria established for each region to determine if the model variogram was an acceptable model. If the model failed, another model variogram was tested until an acceptable model was found or it was determined that no variogram could be fit to the data. The details of the cross validation procedure are discussed in Section 4.4.

4. Once the model variograms were determined for the average ETr data in each month and region, the models were tested in the individual years (1985, 1986, and 1987). The cross validation procedure was performed for the individual years to check the results of using the model variograms from the average ETr applied to the three individual years.

5. The final step in the geostatistical procedure was kriging and contouring the ETr estimates. Using the KRIGE subroutine in GeoEAS and the model variograms for the average ETr data, kriging was done for two months (July and September) of the three year average ETr data in each region. The details on kriging and contouring the ETr data are discussed in Section 4.5

## 4.2 DATA PREPARATION

The initial step of the data preparation was preparing the Geo-EAS ASCII data files. A detailed description of the format is discussed in the user's guide for the Geo-EAS software available through the Environmental Protection Agency (EPA). The monthly data (May through September) furnished for 1985, 1986, and 1987 in each region were used to calculate a three year average of the ETr data. Geo-EAS files were created for the three year average ETr data along with the ETr estimates for the individual years. A data file consisted of ETr estimates provided at the weather stations available in the specific region for a particular month.

Previous research on reference evapotranspiration had already documented that this parameter was a probability variable with a normal distribution (Wright and Jensen, 1972; Nixon et al., 1972). Cuenca (1989) commented that if enough years of daily data are available, the daily evapotranspiration rate can be shown as normally distributed, thus implying the monthly evapotranspiration is also normally distributed. Since reference evapotranspiration was already known to represent a normal distribution, there was concern that possible outliers existed in the data sets. The final step in the data preparation was to explore the ETr estimates looking for outliers which were unrepresentative of the data set. STAT1 provided in Geo-EAS was utilized to produce the normal probability plots of the data. A probability plot is a cumulative frequency plot scaled so that a normal distribution plots as a straight line. By examining the normal probability plots, data points which unquestionably did not lie on the line through the plotted points were identified as outliers and removed from the data set. Once the outliers were removed, the data sets were ready for the variogram analysis.

## 4.3 VARIOGRAM MODELING

The core of geostatistical analysis is in the computation, interpretation, and modeling of the variogram. The variogram attempts to interpret the spatial structure between neighboring variables or measurements, and controls the way the kriging weights are designated to known data points used in interpolating at unknown locations. There are several interpolating and contouring methods which assume that a measurement at any point represents nearby locations better than locations further away. These methods employ an arbitrary weighting factor as a function of distance for the interpolation of the variables to unknown locations. The difference between these methods and geostatistics is that the variogram analysis in geostatistics strives to quantify the spatial relationship of the variance between data points in order to determine the weighting factors.

As seen in Eq. (10), a plot of the semivariance function depicts one half the squared difference (or variance) of the pairs of measurements relative to the distances separating the pairs. The plot of the semivariance function is called the sample variogram. In practice, the semivariance function is calculated for groups of measurement pairs in class intervals of similiar distances and direction (Englund and Sparks, 1988). Using a graphical plot of the variances versus distances for a particular direction, a model variogram is fitted through the plot.

Using VARIO from Geo-EAS, the semivariance functions were calculated and plotted with respect to distances separating the pairs of data. Since the regions used for the analysis were assumed to be homogeneous, a variogram for the region regardless of direction was desired. The direction option from the VARIO analysis consisted of the direction and angular tolerance.

tolerance. Figure 9 illustrates how these settings affect the grouping of pairs within a lag interval. For this work a zero direction with a 90 degree angular tolerance was used. These settings allowed all pairs to be included regardless of direction and maximized the number of pairs in each distance class. The lag intervals used in the geostatistical analysis were determined from a rule of thumb which states that variograms are generally not valid beyond one half the maximum distance between samples (Geo-EAS, 1988). In the VARIO program, the maximum pair distance is divided by two and then subdivided into ten equal distance classes. The above settings used in the analysis were the default values given in VARIO routine of Geo-EAS.

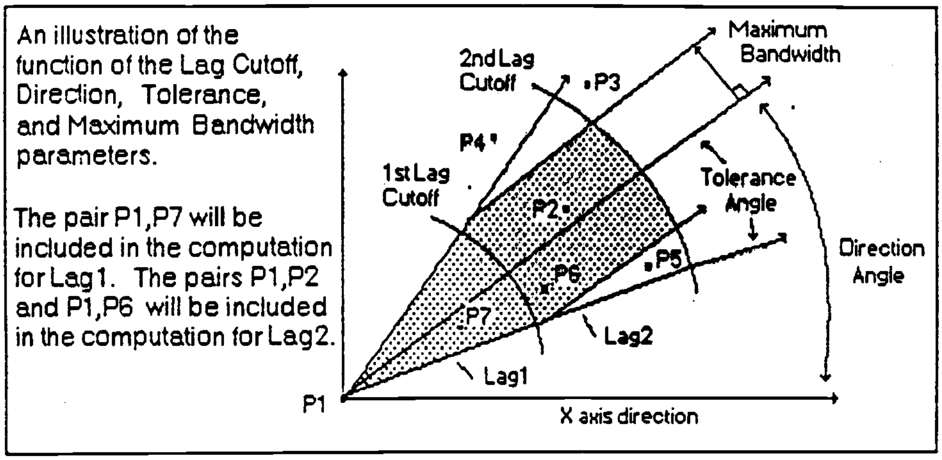



Figure 9: Illustration of Direction Parameters (taken from user guide of Geo-EAS)

From the plotted graph of the variances versus distances, a model variogram was fitted through the data. As discussed in the Literature Review section, four models are commonly most commonly selected variogram model for applications in hydrology, this model was used. To fit a spherical model to the variogram, three parameters needed to be visually estimated from the plot. The three parameters consisted of the nugget ($Co$), sill ($C$), and range ($a$). A modeling option in VARIO allowed the user to estimate these parameters and visually see how the model variogram fitted the data. The best model is selected subjectively by picking the model that appears to have the best fit and at the same time satisfies the quantitative error criteria which is checked in the analysis.

## 4.4 CROSS VALIDATION

Delhomme (1976) proposed a cross validation procedure to determine the best model variogram when ambiguity exists in the model selection. The procedure consists of removing the known variables from the data set one at a time and kriging the remaining known variables to estimate the value at the location of the removed variable. In the cross validation procedure suggested by Delhomme (1976), the model variogram is tested against certain conditions to judge the acceptability of the variogram. These conditions determine if there is a bias in the estimates, if the estimation errors are consistent with the kriging variances, and if the model is an optimal model.

The first condition requires testing the variogram to ensure unbiased estimates and consistency. To be unbiased, the average kriging error (AKE) must close to zero:

$$AKE = \frac{1}{n}\sum_{i=1}^{n}[ET^{*}(x_i) - ET(x_i)] = 0 \tag{29}$$

where

$ET^{*}(x_i)$ = kriged evapotranspiration at $x_i$

$ET(x_i)$ = observed or measured evapotranspiration at $x_i$

n = number of measurements of evapotranpiration over the region of interest

For the kriging errors to be consistent with the kriging variances, the standardized error should be normally distributed with a mean close to zero and a variance close to one (Delhomme, 1976). The mean and variance of the standardized errors can be written as follows:

a) mean of standardized error: $m_{se} = 0$

$$m_{se} = \frac{1}{n}\sum_{i=1}^{n}\{ET^{*}(x_i) - ET(x_i)\}/\sigma_{ki} \tag{30}$$

where $ET^{*}(x_i)$, $ET(x_i)$, and $n$ are previously defined and $\sigma_{ki}$ is the kriging standard deviations.

b) variance of standardized error: $s^2_{se} = 1 \pm 2\sqrt{\left[\frac{2}{n}\right]}$

$$s^2_{se} = \frac{1}{n-1}\sum_{i=1}^{n-1}\left\{[ET^{*}(x_i) - ET(x_i)]^2\right\}/\sigma^2_{ki} \tag{31}$$

where $\sigma^2_{ki}$ is the kriging variances.

The second condition requires determining if the model variogram is optimized by finding the model with the minimum mean squared error (MSE):

$$MSE = \frac{1}{n}\sum_{i=1}^{n}[ET^{*}(x_i) - ET(x_i)]^2 = minimum \tag{32}$$

As a practical rule, the MSE should be less than the variance of the sample values (Cooper, 1986):

$$MSE < \sigma^2 \tag{33}$$

where $\sigma^2$ is equal to the variance of the sample values, ETr. As commented by Cooper (1986), if the MSE is less than the sample variance, the kriging estimate is an improvement over the estimate provided by the mean for all the sample values. It follows that the root mean square error (standard deviation of the kriging errors) should be lower than the standard deviation of the regionalized variable, ETr. Table 3 shows the criteria specified for each region from the cross validation conditions described. The number of stations is approximate since this number varied from month to month within a region.

Table 3: Cross Validation Criteria for each region

| Region | n approx | $S^2_{ee}$ | $m_{ee}$ | AKE | Standard Deviation: Error Variable |
|---|---|---|---|---|---|
| 1 | 21 | $1 \pm 0.6172$ | 0.00 | 0.00 | $S_{error} < S_{var}$ |
| 2 | 39 | $1 \pm 0.4529$ | 0.00 | 0.00 | $S_{error} < S_{var}$ |
| 3 | 16 | $1 \pm 0.7071$ | 0.00 | 0.00 | $S_{error} < S_{var}$ |
| 4 | 42 | $1 \pm 0.4364$ | 0.00 | 0.00 | $S_{error} < S_{var}$ |
| 5 | 51 | $1 \pm 0.3961$ | 0.00 | 0.00 | $S_{error} < S_{var}$ |

The cross validation procedure provides a good method of checking whether the model variogram meets the validation criteria. However caution is required not to assume the model variogram is a valid model only because these conditions are satisfied. The cross validation criteria are necessary but not sufficient conditions for an acceptable model variogram. The last and most important of the criteria in this procedure is that the validated model variogram also closely approximates the sample variogram of the data (Clark, 1986; Journel and Huijbregts,1987).

## 4.5 KRIGING AND MAPPING EVAPOTRANSPIRATION DATA AND ERROR

Kriging and mapping ETr was performed on the average reference evapotranspiration data for 1985, 1986, and 1987. Two types of kriging were possible in the KRIGE routine in Geo-EAS: simple and ordinary. Using the validated model variogram obtained from the cross validation procedure along with the KRIGE routine in the Geo-EAS package, ordinary kriging was performed for two months (July and September) in each region. These two months were chosen to give an illustration for the middle and end of the growing season. In the kriging analysis, ETr was estimated using the weights solved by the kriging system of equations at points of a specified grid superimposed over the region. The kriging standard deviations for the kriged ETr estimates at the grid points were also computed in the KRIGE routine. This standard deviation gives an estimate of the error associated with the kriged ETr estimates.

The KRIGE routine in the Geo-EAS package provides a grid option used to specify the origin of the grid, the size of grid cells, and the number of cells in the X and Y direction. The size of grid cells indicates the distance between points in the grid. The number of cells chosen determines the number of points to be produced in each of the two directions. For each of the regions, the grid spacing chosen was 10 km by 10 km. Amegee (1985) chose a grid size of 12.87 km (8 miles) based upon the fact it has been customary to assume that at distances greater than 16.5 km (10 miles) from a weather station, adjustments may need to be made to ET estimates in order to take into consideration the variability due to distance, surface heterogeneity, and micro-climatic modifications. Since the analysis performed in this work was on a subregional scale, it was decided to reduce the grid size to 10 km to allow smaller regions to have an adequately dense grid of the kriged ETr estimates.

For the mapping of the kriged estimates of ETr and standard deviations, a contouring software package, SURFER, was utilized. The gridded information on kriged ETr and standard deviation for regions providing validated model variograms was imported into SURFER along with a boundary file representing the outline of the region. The SURFER package was used to draw isolines through the gridded information along with an outline of the region.

# 5 RESULTS AND DISCUSSION

This chapter presents results obtained from analysis of monthly reference evapotranspiration (ETr) estimates for the regions representing the state of Oregon. The first two sections discuss data analysis and preparation which preceded the geostatistical analysis. Following these sections, results of the variogram and cross validation analysis, outcome of using model variograms obtained from average ETr estimates as the model variograms for the ETr estimates in the individual years, and kriging and mapping the kriged ETr along with the error associated with the kriged estimate are discussed. Alternate notation for reference evapotranspiration (ETo) given by Doorenbos and Pruitt (1977) was used in certain figures presented in this chapter. In any case, the reference crop is always grass.

## 5.1 SAMPLE VARIANCE

The sample variance was calculated for each data set. A data set consisted of ETr estimates for a particular month and region in a given year or average of the three years. Table 4 presents the sample variances calculated for each data set. The sample variances were used to determine a reasonable maximum value of the model variogram. As indicated in the Literature Review, by definition the sample variance is theoretically the maximum value of the sample variogram.

TABLE 4: Sample Variance of ETr for each month for each year in each region

| | May | June | July | August | September |
|---|---|---|---|---|---|
| Region 1: | | | | | |
| 1985 | 0.0350 | 0.0456 | 0.109 | 0.0490 | 0.0387 |
| 1986 | 0.0436 | 0.0635 | 0.0462 | 0.1106 | 0.0460 |
| 1987 | 0.0556 | 0.0388 | 0.0510 | 0.0836 | 0.0348 |
| 3 yr Ave | 0.0331 | 0.0513 | 0.0629 | 0.0707 | 0.0243 |
| Region 2: | | | | | |
| 1985 | 0.0846 | 0.0487 | 0.0677 | 0.0572 | 0.0301 |
| 1986 | 0.0640 | 0.0395 | 0.0751 | 0.0506 | 0.0280 |
| 1987 | 0.0786 | 0.0556 | 0.0726 | 0.0723 | 0.0377 |
| 3 yr Ave | 0.0747 | 0.0453 | 0.0681 | 0.0561 | 0.0390 |
| Region 3: | | | | | |
| 1985 | 0.3290 | 0.4570 | 0.2435 | 0.2570 | 0.1484 |
| 1986 | 0.3273 | 0.4486 | 0.3280 | 0.3276 | 0.1360 |
| 1987 | 0.3326 | 0.4706 | 0.2733 | 0.3213 | 0.0827 |
| 3 yr Ave | 0.3241 | 0.4600 | 0.2636 | 0.3293 | 0.1164 |
| Region 4: | | | | | |
| 1985 | 0.1573 | 0.2709 | 0.1086 | 0.1055 | 0.1002 |
| 1986 | 0.1216 | 0.1252 | 0.0784 | 0.1043 | 0.0763 |
| 1987 | 0.1543 | 0.2508 | 0.0817 | 0.2152 | 0.0712 |
| 3 yr Ave | 0.1510 | 0.1420 | 0.0728 | 0.1458 | 0.1089 |
| Region 5: | | | | | |
| 1985 | 0.2960 | 0.3850 | 0.3702 | 0.1613 | 0.1127 |
| 1986 | 0.1984 | 0.4134 | 0.4186 | 0.1890 | 0.1248 |
| 1987 | 0.2681 | 0.3083 | 0.3983 | 0.1728 | 0.1314 |
| 3 yr Ave | 0.1857 | 0.3424 | 0.4481 | 0.1601 | 0.1361 |

## 5.2 DATA PREPARATION

The first step in data analysis is to become familiar with the data set. This includes exploring distributions of the data throughout the area of interest, computing the statistics of the data, and observing other characteristics. As discussed in the Procedure section, the data used in this project were examined for outliers which were unrepresentative of the data sets. The procedure for locating these outliers consisted of investigating normal probability plots of the data. Figure 10 provides an example of a normal probability plot from the average ETr estimates for August in region 1. One can see from the plot that an outlier exists for this data set (i.e. one data point clearly does not lay on the straight line representing a normal distribution of the data). Any data values representing outliers, such as seen Figure 10, were removed from their respective data sets.

An example of a data set not showing outliers can be seen in Figure 11. This figure represents the normal prabability plot for the average ETr estimates for September in region 5. As seen in the figure, the data are normally distributed along a straight line.

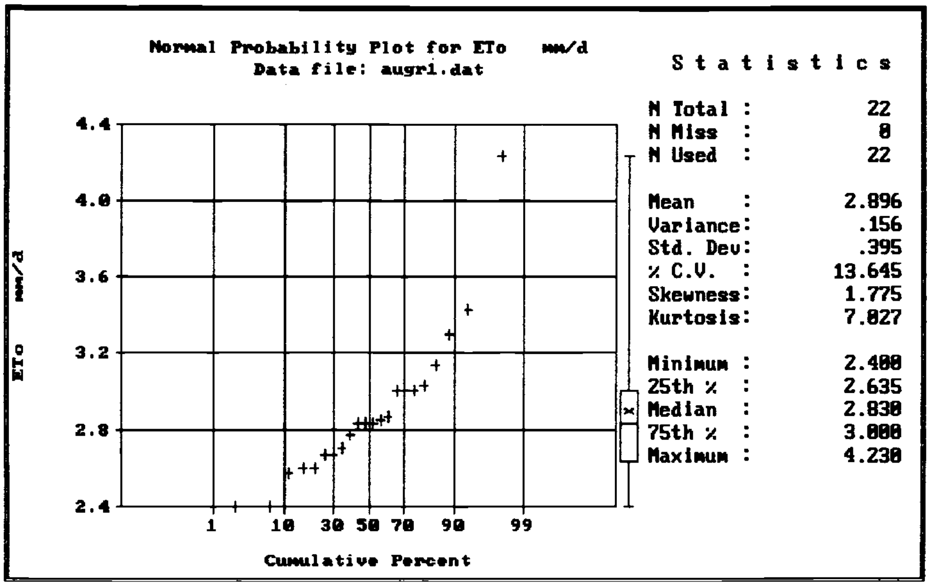



Figure 10: Normal Probability Plot for Ave. ETr in August, Region 1

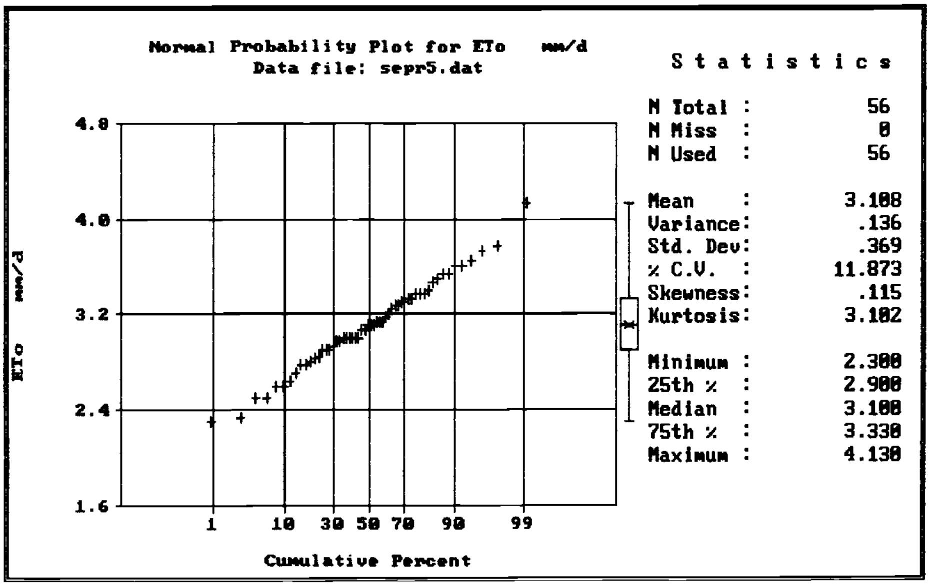



Figure 11: Normal Probability Plot for Ave. ETr in September, Region 5

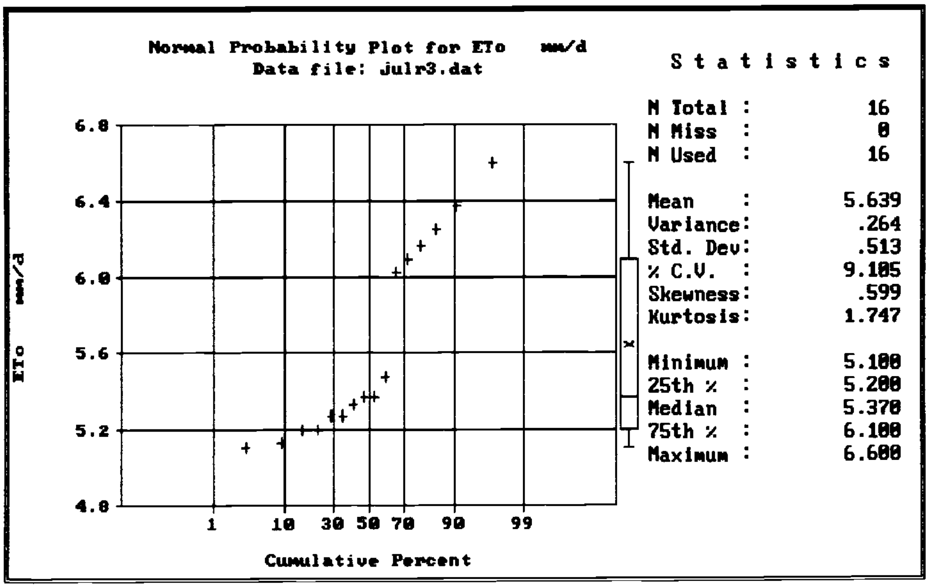



Figure 12: Normal Probability Plot for Ave. ETr in July, Region 3

Normal probability plots for four out of five regions showed the data to be normally distributed and outliers were easily identified. The region not representing a normal distribution for the data was region 3. Figure 12 is the normal probability plot for July in region 3. Since from previous research ETr is known to be normally distributed, this plot suggests that not enough data points exist to adequately define the distribution. Devore and Peck (1986) commented that normal probability plots from small sample sizes can have substantial departures from a straight line even when the distribution is normal. The plot might also suggest region 3 should be divided into two regions. A closer examination into the location ETr estimates falling along the two apparent lines could aid in this decision. Region 3 remained in the geostatistical analysis, but it was anticipated that this region would not yield good results.

## 5.3 VARIOGRAM/CROSS VALIDATION RESULTS

Sample variograms were calulated for each month and region. Using the modeling option provided in VARIO, model variograms were fitted to the sample variograms. Model variograms were first subjectively fit through the cloud of points representing the sample variograms and then tested by the cross validation procedure. The model variogram selected was that which satisfied the criteria established in the cross validation procedure and which appeared to best fit the sample variogram. The model variograms selected to fit the sample variograms for each month and region are shown in Figures 13 through 17. The X axis in these figures represent the distances, *h* in km, separating the data pairs used to calculate the semivariance function. The results of the cross validation analysis for these models are found in Table 5. It should be noted that the sample variances shown under parameters in the figures are not always representative of the actual sample variance. A bug in the Geo-EAS program is considered the reason for this error.

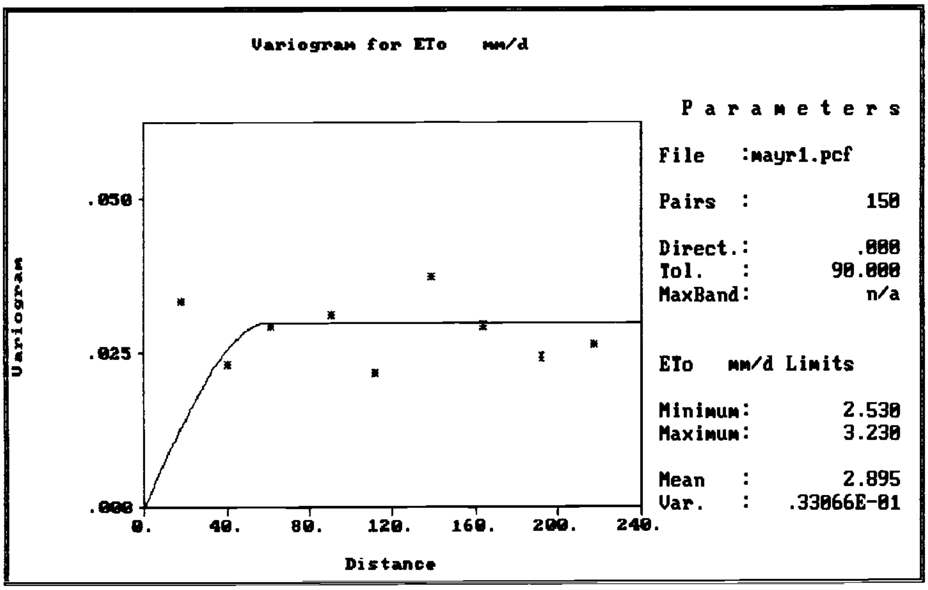
The spherical model was selected as the model variogram to be used based on its wide application in hydrology. In general, the sample variograms for the different regions and months within the regions exhibited the characteristics of a spherical model. There were some cases that the sample variogram represented what is called a pure nugget model. However, spherical models were still used in these cases because it was assumed that had there been more data pairs to compute the first point on the sample variogram, the variogram could be represented by a spherical model. For some regions, there was considerable variability seen in the sample variograms. One of the expected reasons for this variability was the lack of enough samples to represent the spatial distribution of the data adequately. This was particularly noticable in region 3.

As discussed earlier, the spherical model requires visualizing the nugget ($Co$), sill ($C$) and range ($a$) from the sample variogram. The sample variance was calculated to help define the possible maximum value of the sample variograms. For four out of five regions, the maximum value of the sample variograms approached the sample variance. However, this is not a requirement of a valid sample semvariogram. Only the model variograms representing the sample variograms in region 5 had a maximum value less than the sample variance.

Since the nugget is associated with the error of the estimation or measurement of the variable at a point and there are known errors related to the reference evapotranspiration estimate, one would expect to see evidence of a nugget effect. For regions 1 and 3, it was difficult to discern a nugget in the sample variogram, therefore a zero nugget was used in the spherical model. If there had been a way to know the estimation errors associated with the FAO-modified Blaney Criddle method, a minimum value for the nuggect could have been stipulated. The other three regions (2, 4, and 5) showed a nugget effect due to the expected error of the estimates. Within these three regions, the nugget was not constant for every month. One would not necessarily expect the nugget to be constant. The fact that each month did not always have the same number of ETr estimates and the varying magnitude of this estimate could explain this shifting nugget.

The range of the spherical model represents the limit of influence of the sample variogram. At distances greater than the range, geostatistics provides no relationship for the spatial structure of the variable. One could also remark that the range gives an indication of the distance the estimates of ETr obtained at a weather station influences ETr within the region. There was not a fixed pattern in the variation of the range by month for each region. In general, the range started with a low value in May, increased during the warmest part of the growing season, and then decreased to a low value again in September. There were certain anomalies in the range with large variations between months, particularly in region 4. There is no clear reason for this anomaly. The final range selected was the value which best satisfied the cross validation criteria.

The results of the cross validation of the model selected for each month within the individual regions are given in Table 5. For four out of five regions, the selected models met the criteria of the cross validation tests. The values for the averaged kriged error (AKE) and mean of the standardize error ($m_{\bullet\bullet}$) in region 3 are larger (i.e. diverge more from zero) than those obtained in the other regions. Therefore, it was difficult to confirm that the model variograms for this region were valid. From the distinct disparity seen in the normal probability plots and the small sample size of this region, it was not surprising that variograms were not able to be modeled to the data. This region was eliminated from the kriging and mapping of the ETr.



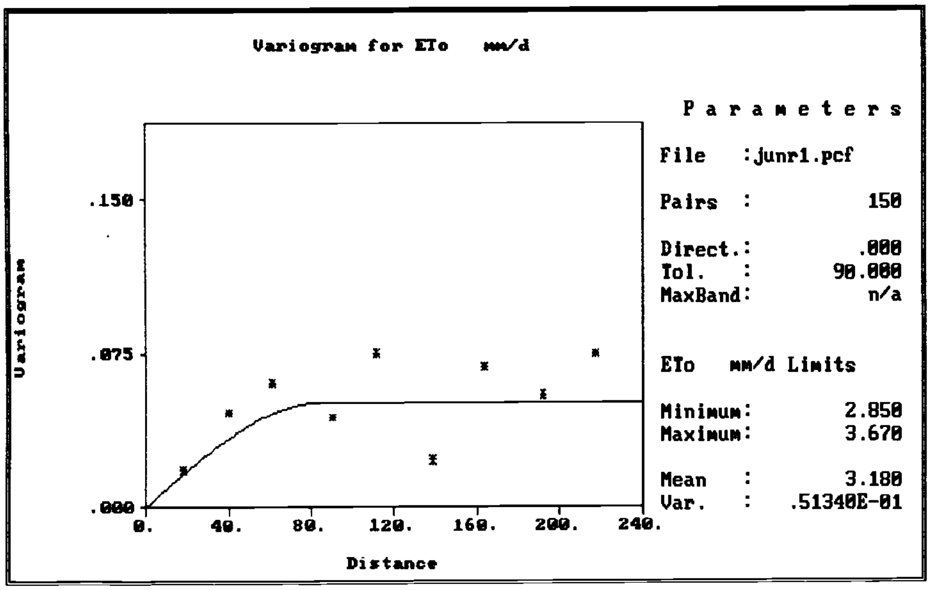
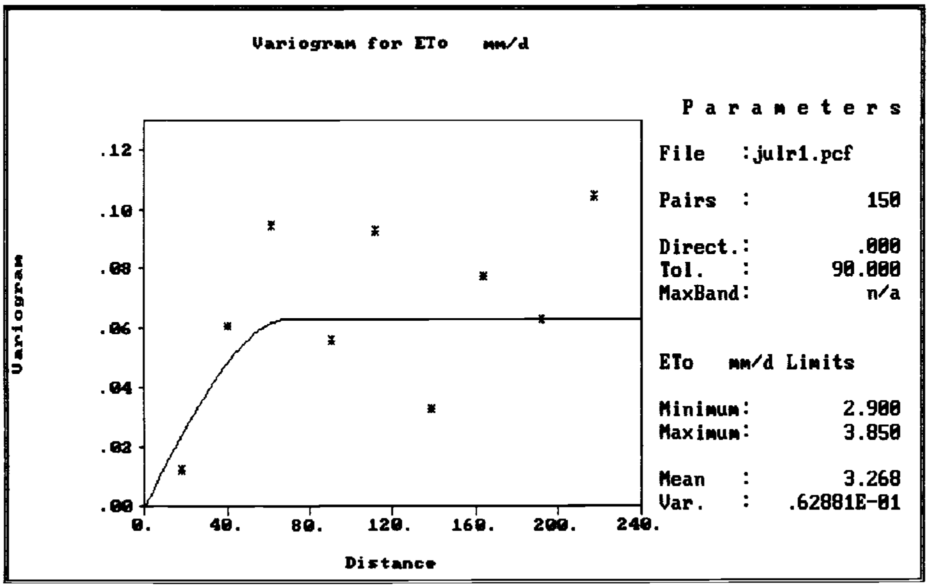




Figure 13: Variograms for Region 1



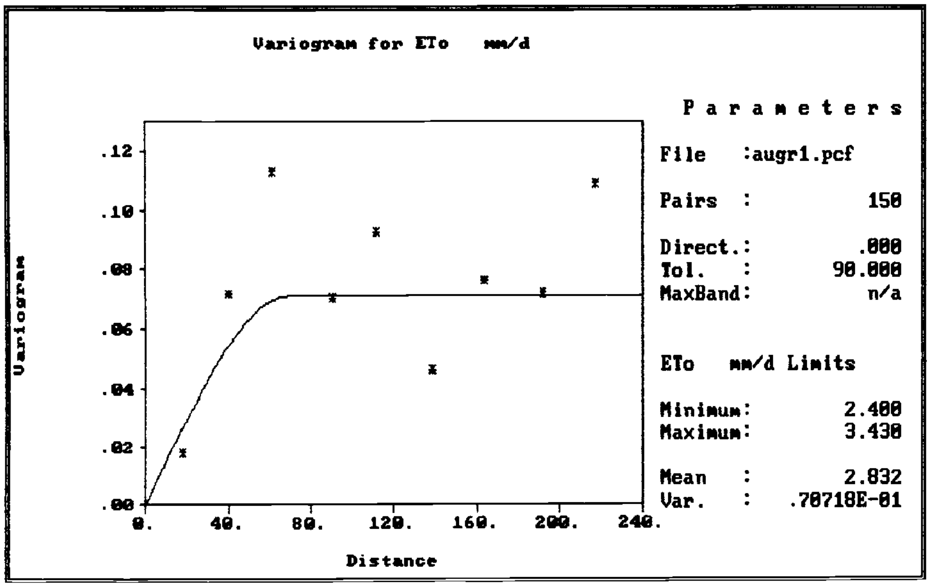




Figure 13: cont.

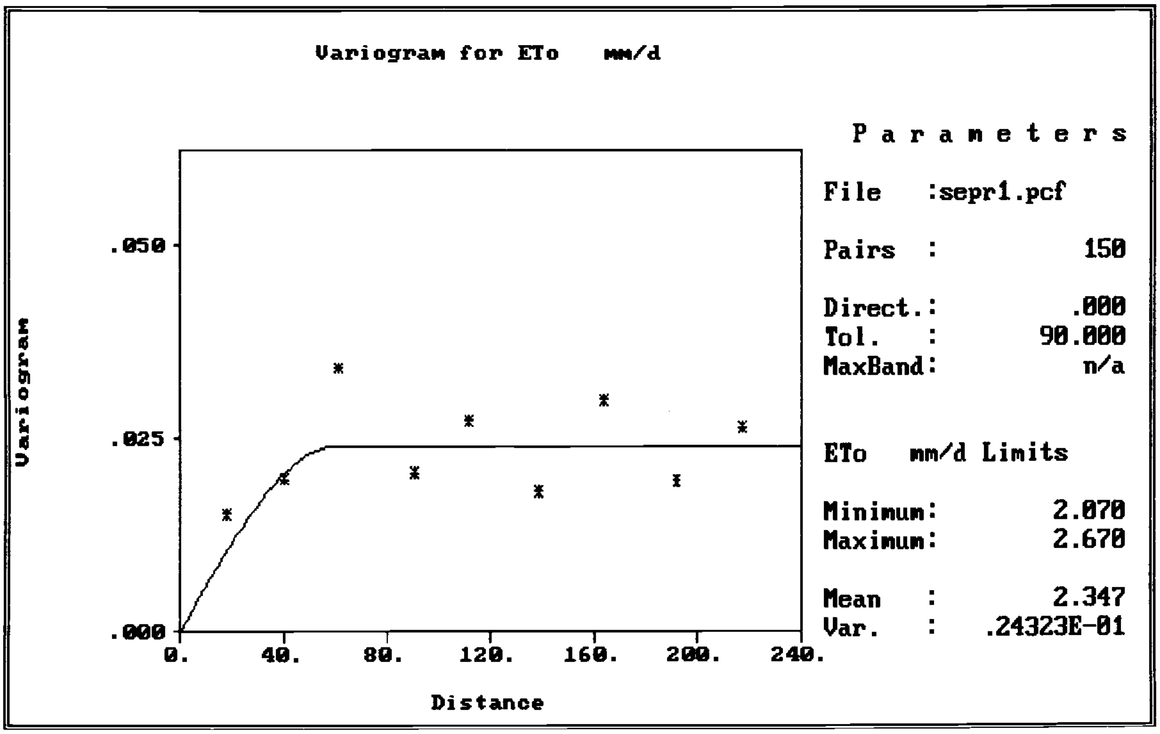
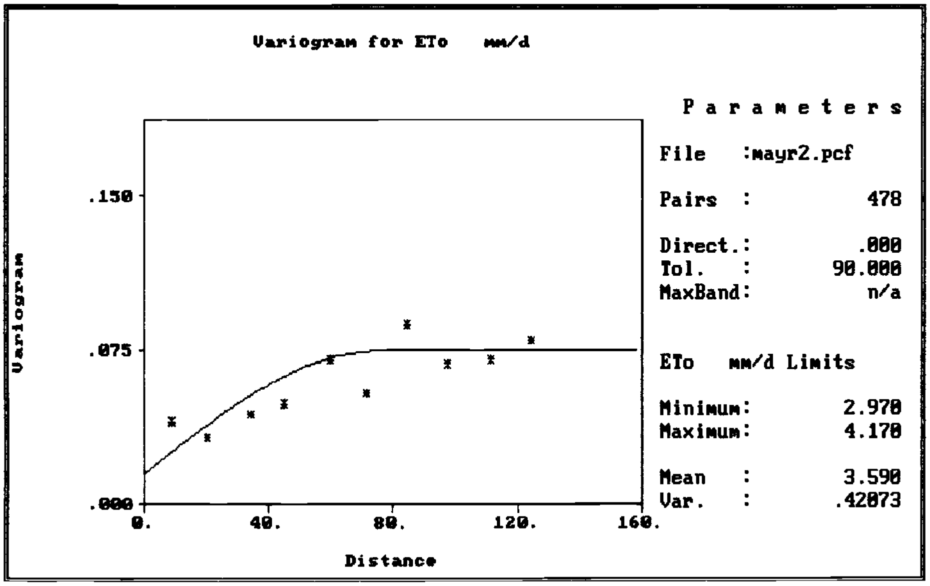



Figure 13: cont.



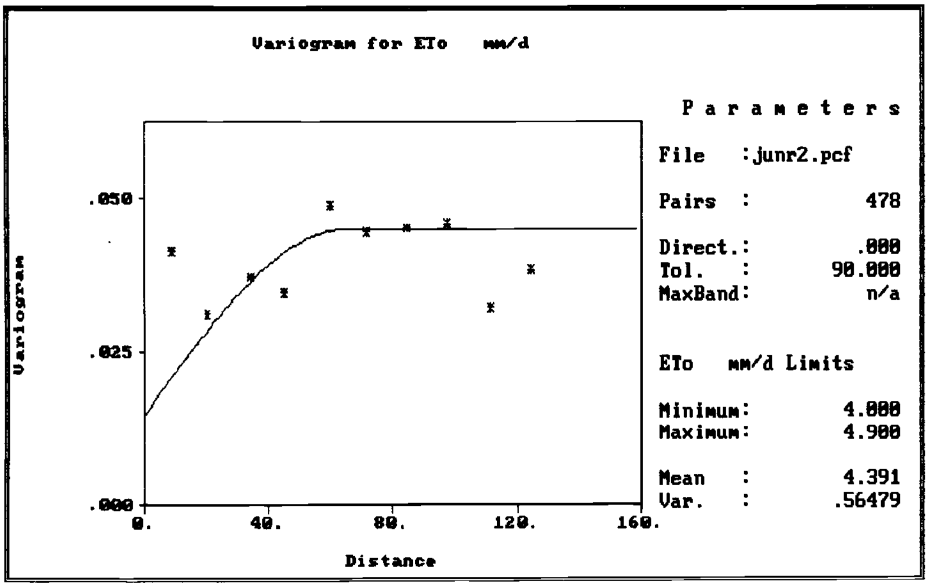
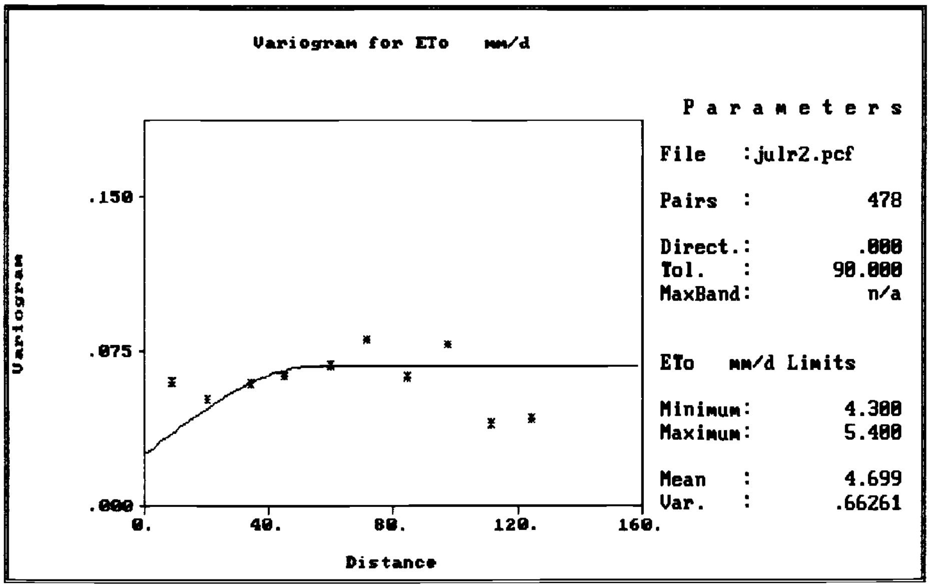




Figure 14: Variograms for Region 2
Semi



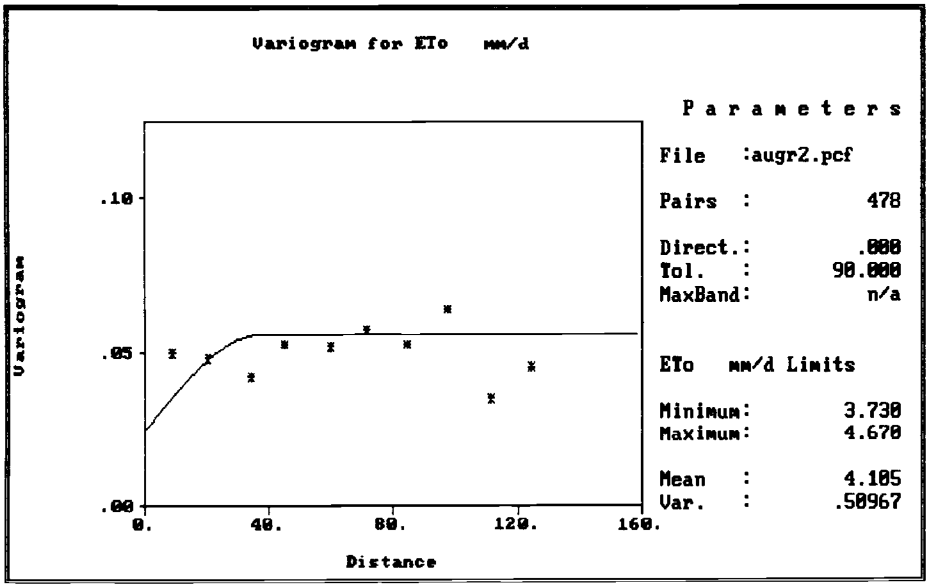




Figure 14: cont.

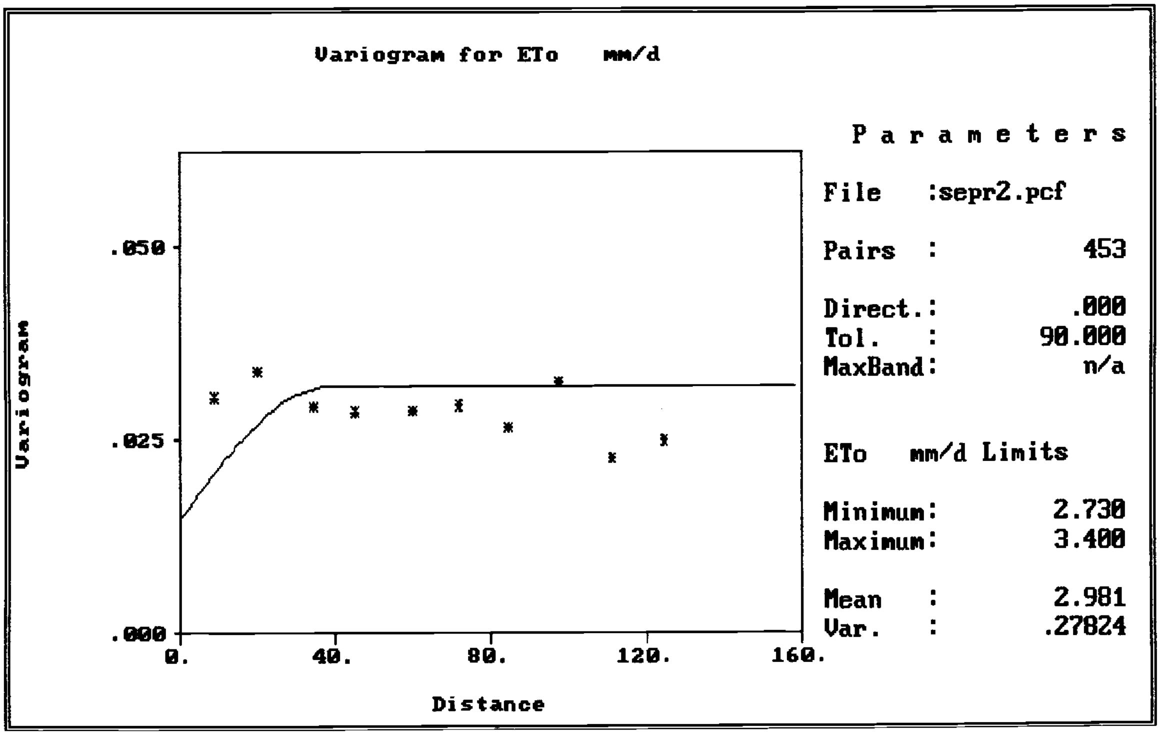
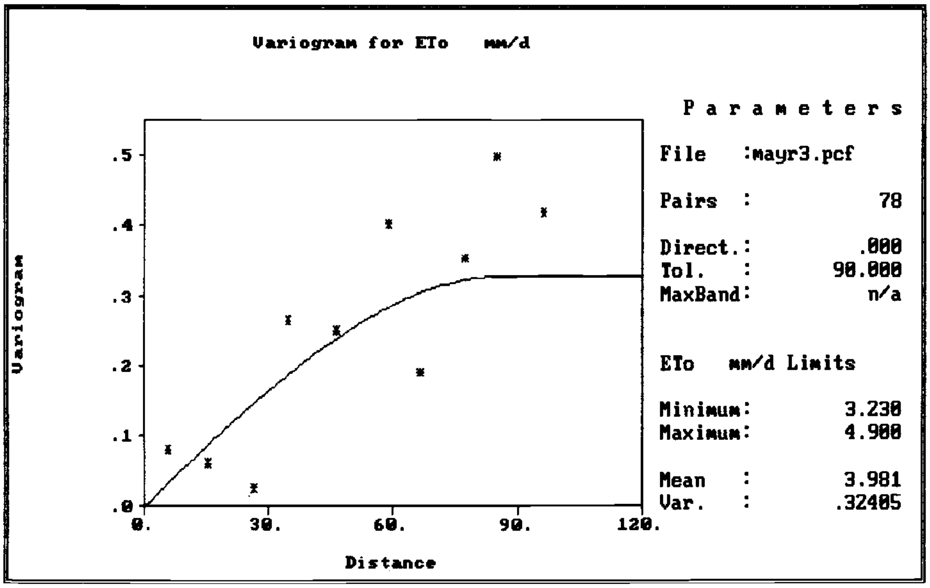



Figure 14: cont.



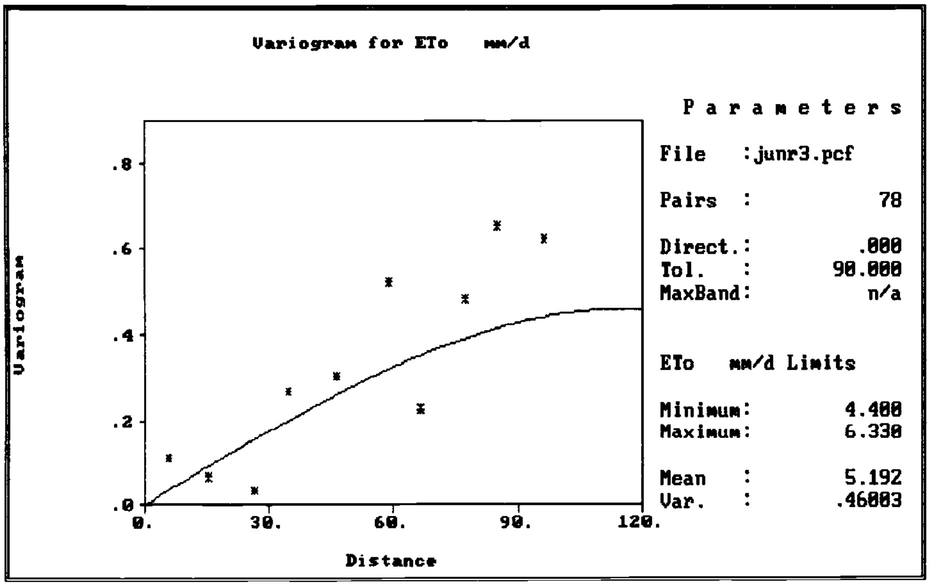
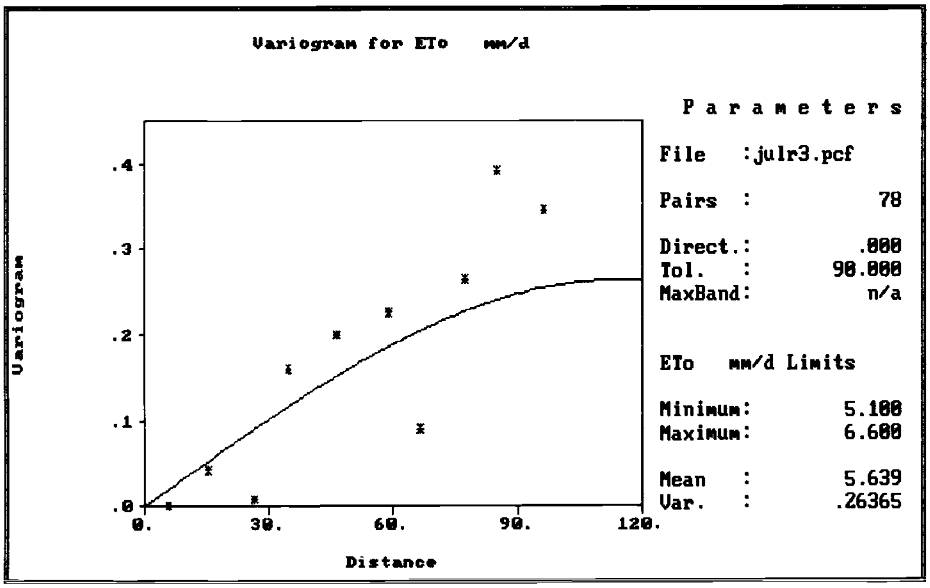




Figure 15: Variograms for Region 3

Semi



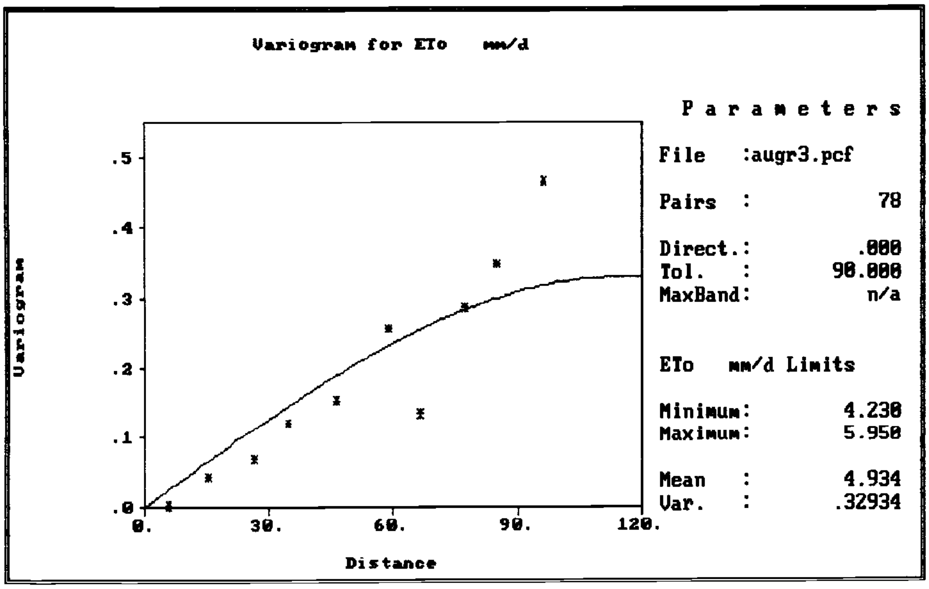




Figure 15: cont.

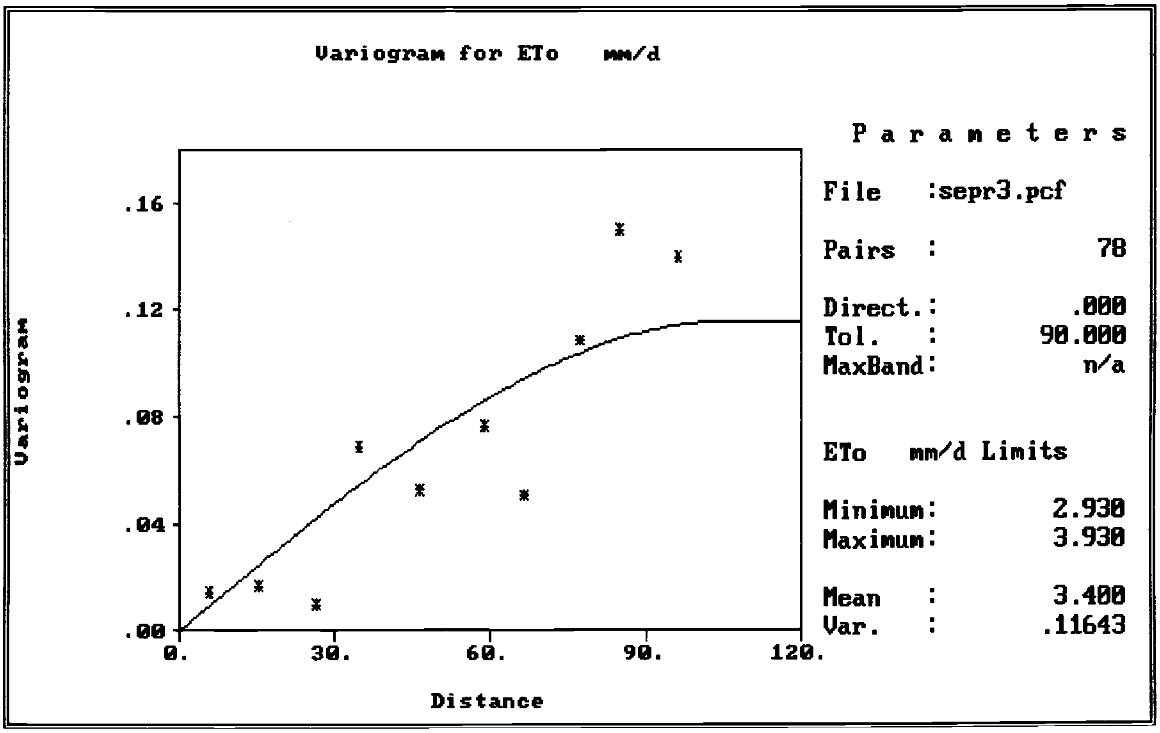
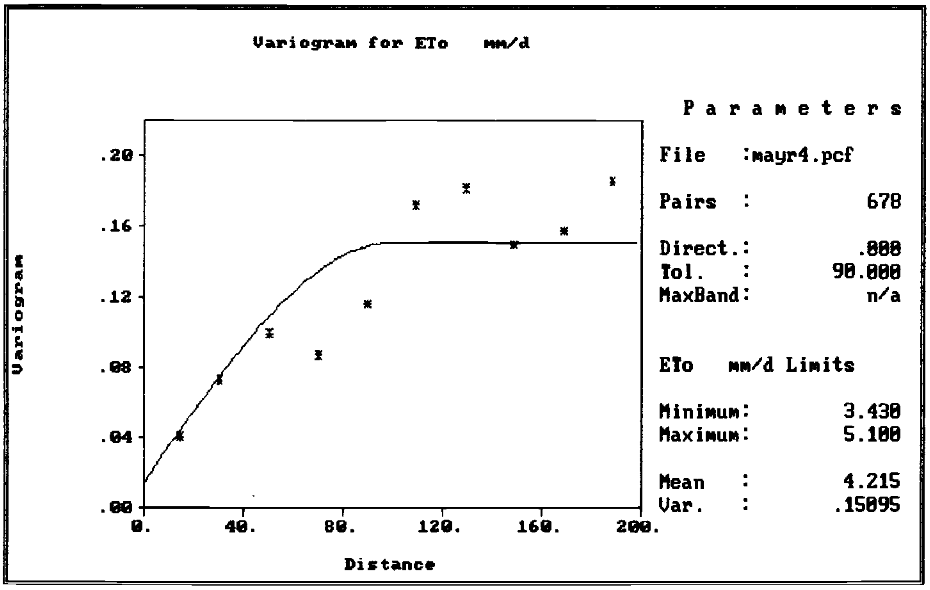



Figure 15: cont.



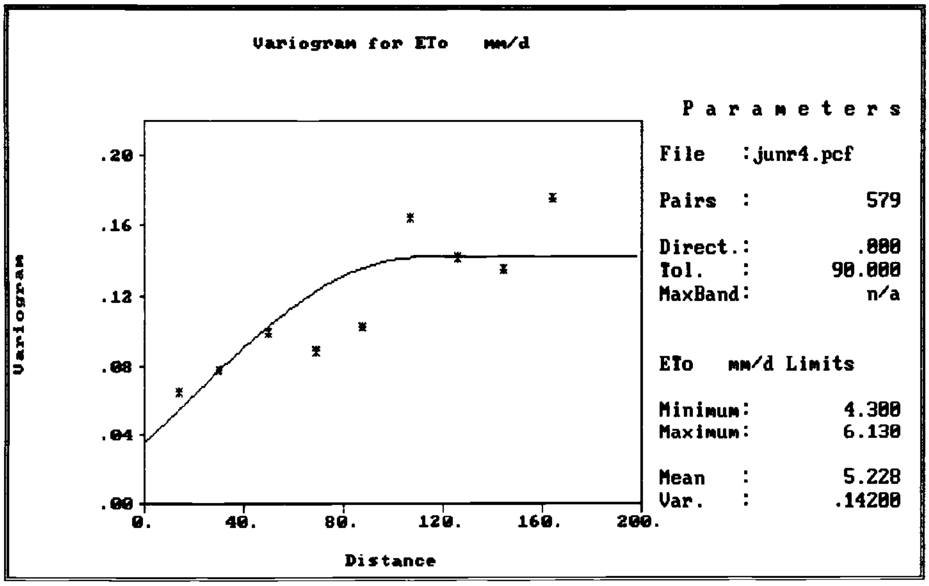
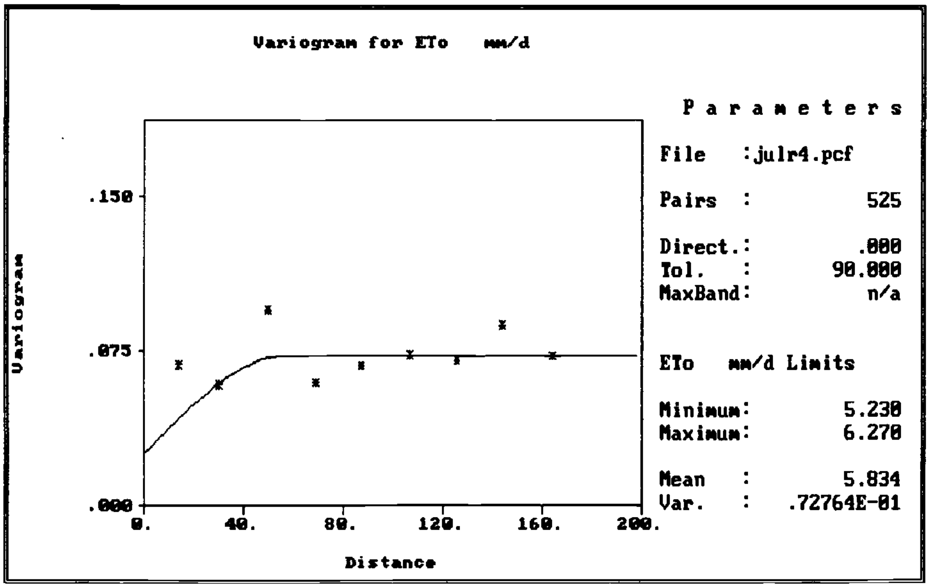




Figure 16: Variograms for Region 4

Semi



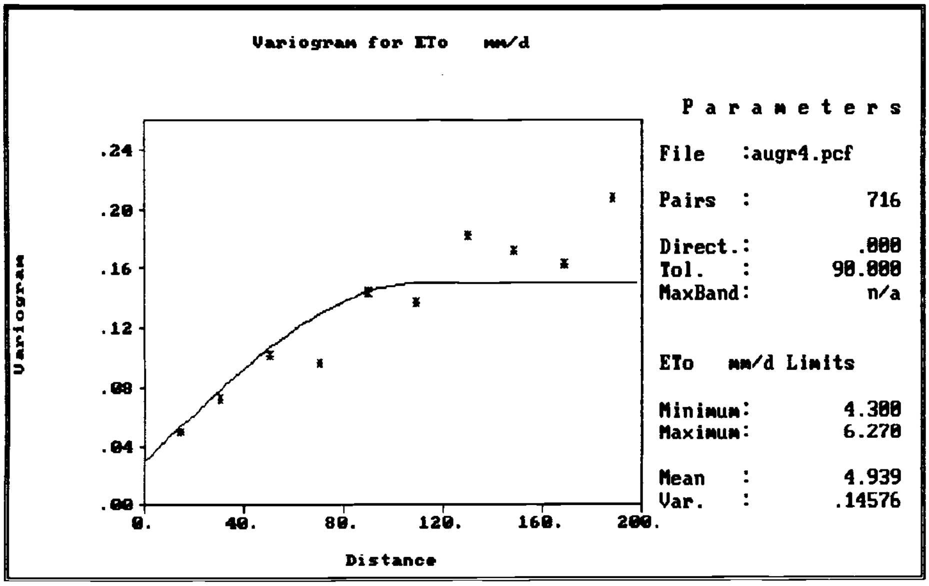




Figure 16: cont.

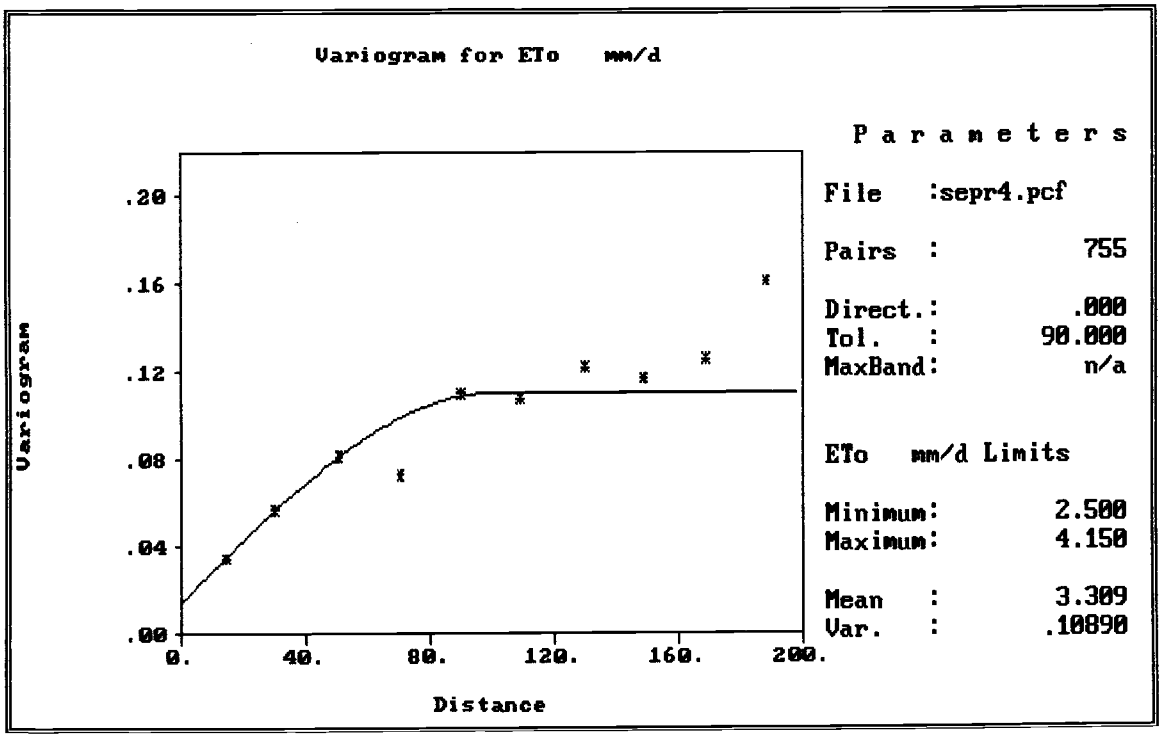
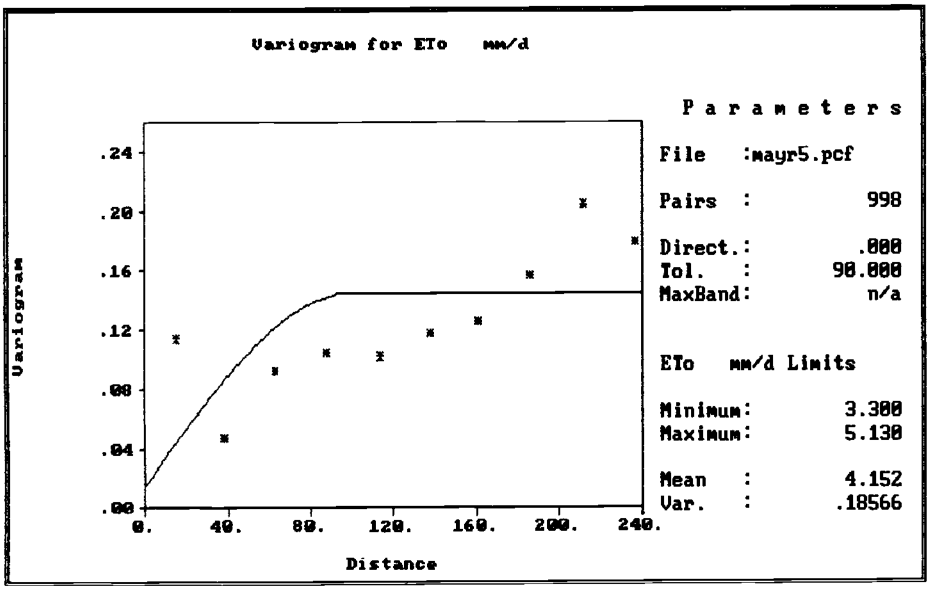



Figure 16: cont.



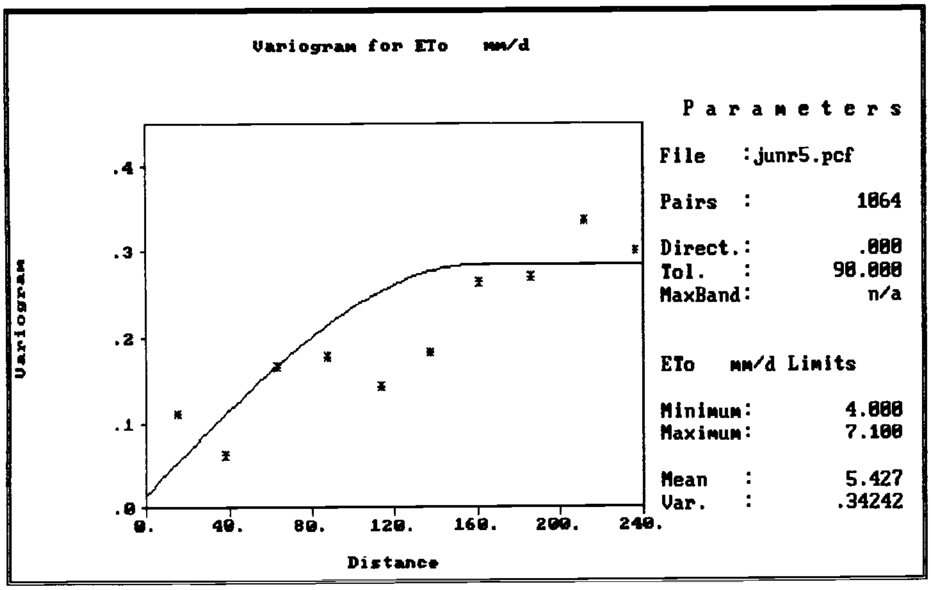
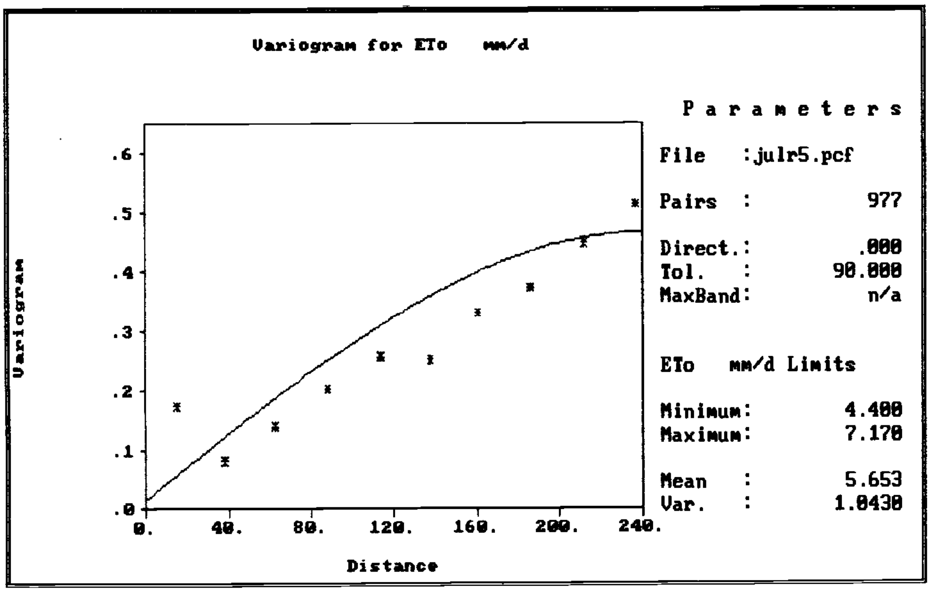




Figure 17: Variograms for Region 5
semi



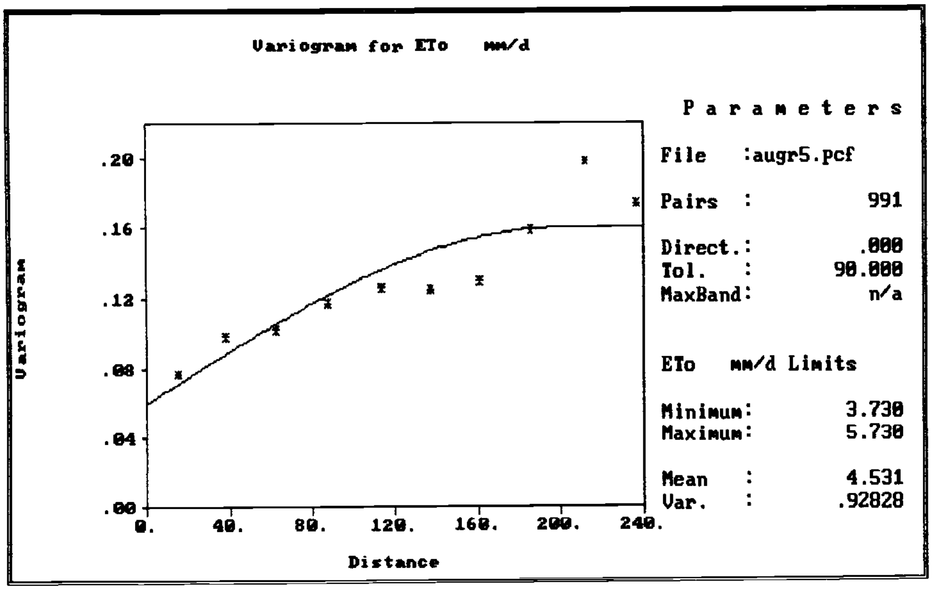




Figure 17: cont.

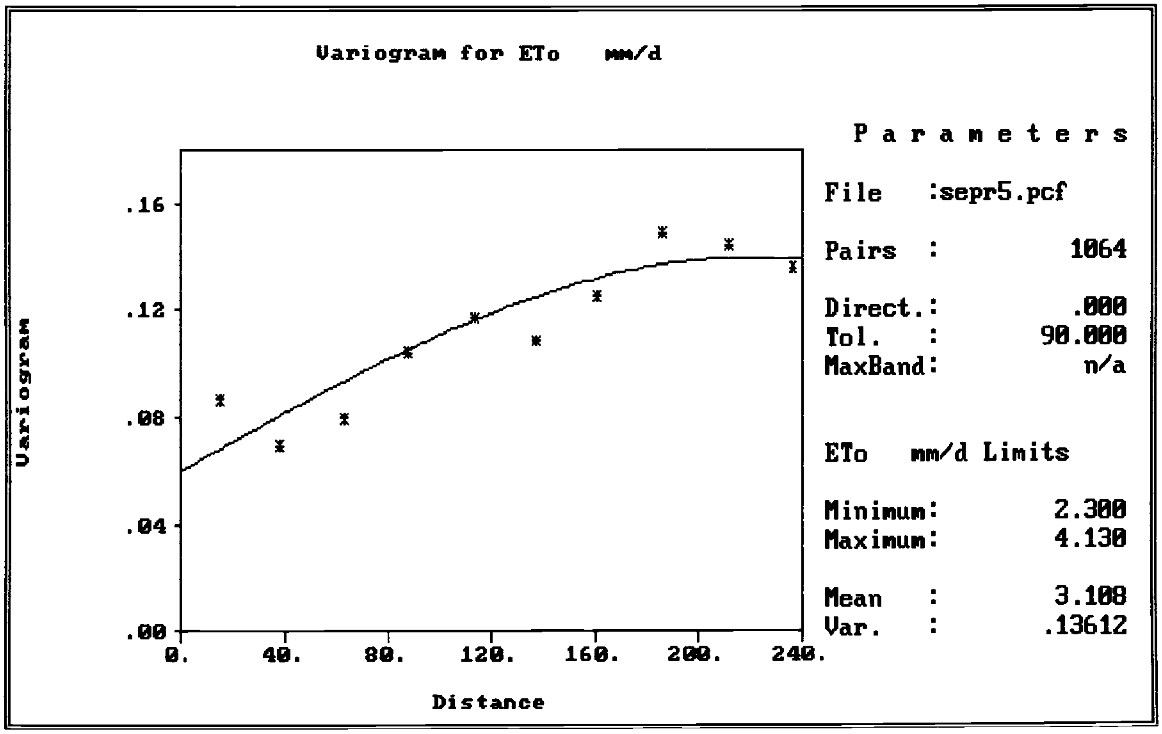



Figure 17: cont.

Table 5: Variogram and Cross Validation Results

| | | AKE | $m_{se}$ | $S^2_{se}$ | Standard error | Deviation variable | VARIOGRAM:spherical model NUGGET | RANGE | SILL |
|---|---|---|---|---|---|---|---|---|---|
| **REGION 1: COASTAL** | | | | | | | | | |
| **3YR AVERAGE DATA** | | | | | | | | | |
| | MAY | -0.019 | -0.088 | 1.077 | 0.173 | 0.182 | 0.000 | 60.0 | 0.030 |
| | JUNE | 0.008 | 0.026 | 1.128 | 0.217 | 0.227 | 0.000 | 85.0 | 0.052 |
| | JULY | 0.008 | 0.027 | 1.030 | 0.239 | 0.251 | 0.000 | 70.0 | 0.063 |
| | AUGUST | 0.004 | 0.008 | 1.072 | 0.262 | 0.266 | 0.000 | 70.0 | 0.071 |
| | SEPTEMBER | 0.010 | -0.047 | 1.002 | 0.145 | 0.156 | 0.000 | 65.0 | 0.024 |
| **REGION 2: WILLAMETTE VALLEY** | | | | | | | | | |
| **3YR AVERAGE DATA** | | | | | | | | | |
| | MAY | 0.005 | 0.018 | 1.148 | 0.232 | 0.273 | 0.015 | 75.0 | 0.060 |
| | JUNE | 0.010 | 0.042 | 1.186 | 0.208 | 0.213 | 0.015 | 65.0 | 0.030 |
| | JULY | 0.000 | -0.005 | 1.071 | 0.240 | 0.261 | 0.025 | 55.0 | 0.043 |
| | AUGUST | -0.002 | -0.016 | 1.005 | 0.224 | 0.237 | 0.025 | 37.0 | 0.031 |
| | SEPTEMBER | 0.006 | 0.022 | 1.000 | 0.169 | 0.180 | 0.015 | 38.0 | 0.017 |
| **REGION 3: SOUTHWESTERN** | | | | | | | | | |
| **3YR AVERAGE DATA** | | | | | | | | | |
| | MAY | 0.089 | 0.098 | 0.999 | 0.413 | 0.569 | 0.000 | 86.0 | 0.327 |
| | JUNE | 0.081 | 0.085 | 0.998 | 0.393 | 0.678 | 0.000 | 116.0 | 0.460 |
| | JULY | 0.072 | 0.104 | 0.998 | 0.340 | 0.513 | 0.000 | 114.0 | 0.264 |
| | AUGUST | 0.056 | 0.076 | 0.791 | 0.302 | 0.574 | 0.000 | 114.0 | 0.329 |
| | SEPTEMBER | 0.047 | 0.101 | 1.000 | 0.230 | 0.341 | 0.000 | 107.0 | 0.116 |
| **REGION 4: NORTHEASTERN** | | | | | | | | | |
| **3YR AVERAGE DATA** | | | | | | | | | |
| | MAY | -0.021 | -0.047 | 1.153 | 0.353 | 0.389 | 0.015 | 100.0 | 0.136 |
| | JUNE | -0.011 | -0.027 | 1.147 | 0.346 | 0.377 | 0.035 | 110.0 | 0.107 |
| | JULY | -0.006 | -0.031 | 1.045 | 0.270 | 0.270 | 0.025 | 57.0 | 0.048 |
| | AUGUST | -0.025 | -0.049 | 1.086 | 0.338 | 0.382 | 0.030 | 110.0 | 0.120 |
| | SEPTEMBER | -0.008 | -0.020 | 1.187 | 0.300 | 0.330 | 0.015 | 100.0 | 0.095 |
| **REGION 5: SOUTHEASTERN** | | | | | | | | | |
| **3YR AVERAGE DATA** | | | | | | | | | |
| | MAY | 0.002 | -0.003 | 1.170 | 0.297 | 0.431 | 0.015 | 100.0 | 0.130 |
| | JUNE | -0.009 | -0.019 | 1.180 | 0.327 | 0.585 | 0.015 | 160.0 | 0.270 |
| | JULY | -0.008 | -0.015 | 1.125 | 0.381 | 0.670 | 0.015 | 240.0 | 0.450 |
| | AUGUST | -0.013 | -0.038 | 1.076 | 0.336 | 0.400 | 0.060 | 200.0 | 0.100 |
| | SEPTEMBER | -0.005 | -0.019 | 0.993 | 0.298 | 0.369 | 0.060 | 220.0 | 0.080 |

## 5.4 COMPARISON WITH YEARLY DATA

For geostatistics to be operational in estimating regional evapotranspiration, it is desirable to have one model variogram that would be representative of the spatial correlation between known weather stations giving local estimates of ETr for the region. This model could allow for real time analysis of regional ETr by removing the time consuming and complicated variogram analysis. To test this hypothesis, a model variogram for each month within the various regions was determined for the average ETr estimates. These model variograms were then used as the model variograms for the individual years (1985,1986, and 1987). The cross validation procedure was performed to determine the validity of using these models.

Tables 6 through 9 give the results obtained from the cross validation test. The model variograms used for each month, year, and region satisfied the cross validation criteria over fifty percent of the time. However, there was no consistency to when the model variograms satisfied or failed the criteria. All the regions except for region 5 had at least one time that the model failed the criteria. Regions 1 and 3 exhibited the worst results from the cross validation analysis using the model variograms from the average ETr estimates.

Why some model variograms from average ETr estimates failed in the analysis of the individual years and others did not might be a consequence of climatic factors rather than geostatistics. The average ETr estimates were taken for only the three individual years. By developing the model variogram from long term average ETr estimates, the model might represent the region more accurately and provide better results when applied to individual years.

Table 6: Cross Validation Results for Region 1, Yearly Data

| | | | | | Standard | Deviation | VARIOGRAM:spherical model | | |
|---|---|---|---|---|---|---|---|---|---|
| | | AKE | $m_{se}$ | $s^2_{se}$ | error | variable | NUGGET | RANGE | SILL |
| 1985 | MAY | -0.024 | -0.112 | 1.046 | 0.164 | 0.187 | 0.000 | 60.0 | 0.030 |
| | JUNE | -0.001 | -0.005 | 1.040 | 0.195 | 0.214 | 0.000 | 85.0 | 0.052 |
| | JULY | -0.019 | 0.059 | 1.273 | 0.301 | 0.322 | 0.000 | 70.0 | 0.063 |
| | AUGUST | -0.006 | -0.021 | 0.982 | 0.236 | 0.221 | 0.000 | 70.0 | 0.071 |
| | SEPT | -0.019 | -0.091 | 1.804 | 0.244 | 0.197 | 0.000 | 60.0 | 0.024 |
| 1986 | MAY | -0.010 | -0.048 | 1.425 | 0.227 | 0.209 | 0.000 | 60.0 | 0.030 |
| | JUNE | 0.015 | 0.053 | 1.272 | 0.247 | 0.252 | 0.000 | 85.0 | 0.052 |
| | JULY | -0.001 | -0.005 | 0.977 | 0.213 | 0.215 | 0.000 | 70.0 | 0.063 |
| | AUGUST | 0.013 | -0.038 | 1.202 | 0.300 | 0.333 | 0.000 | 70.0 | 0.071 |
| | SEPT | 0.021 | -0.105 | 1.961 | 0.266 | 0.214 | 0.000 | 60.0 | 0.024 |
| 1987 | MAY | -0.019 | -0.099 | 1.787 | 0.291 | 0.236 | 0.000 | 60.0 | 0.030 |
| | JUNE | 0.007 | 0.025 | 1.046 | 0.213 | 0.197 | 0.000 | 85.0 | 0.052 |
| | JULY | 0.000 | 0.006 | 0.931 | 0.223 | 0.226 | 0.000 | 70.0 | 0.063 |
| | AUGUST | -0.001 | 0.001 | 1.261 | 0.304 | 0.289 | 0.000 | 70.0 | 0.071 |
| | SEPT | 0.000 | 0.002 | 1.303 | 0.190 | 0.187 | 0.000 | 60.0 | 0.024 |

Table 7: Cross Validation Results for Region 2, Yearly Data

| | | | | | Standard | Deviation | VARIOGRAM:spherical model | | |
|---|---|---|---|---|---|---|---|---|---|
| | | AKE | $m_{se}$ | $s^2_{se}$ | error | variable | NUGGET | RANGE | SILL |
| 1985 | MAY | 0.005 | 0.019 | 1.169 | 0.238 | 0.291 | 0.015 | 75.0 | 0.060 |
| | JUNE | 0.003 | 0.013 | 1.258 | 0.224 | 0.221 | 0.015 | 65.0 | 0.030 |
| | JULY | -0.002 | -0.014 | 1.087 | 0.243 | 0.260 | 0.025 | 55.0 | 0.043 |
| | AUGUST | -0.002 | -0.011 | 1.029 | 0.233 | 0.239 | 0.025 | 37.0 | 0.031 |
| | SEPT | 0.004 | 0.020 | 1.025 | 0.159 | 0.173 | 0.015 | 38.0 | 0.010 |
| 1986 | MAY | 0.002 | 0.010 | 1.114 | 0.230 | 0.253 | 0.015 | 75.0 | 0.060 |
| | JUNE | 0.010 | 0.040 | 1.060 | 0.184 | 0.199 | 0.015 | 65.0 | 0.030 |
| | JULY | 0.000 | -0.003 | 1.077 | 0.246 | 0.274 | 0.025 | 55.0 | 0.043 |
| | AUGUST | -0.004 | -0.023 | 0.935 | 0.210 | 0.225 | 0.025 | 37.0 | 0.031 |
| | SEPT | 0.005 | 0.024 | 0.925 | 0.147 | 0.167 | 0.015 | 38.0 | 0.010 |
| 1987 | MAY | 0.006 | 0.021 | 1.221 | 0.246 | 0.280 | 0.015 | 75.0 | 0.060 |
| | JUNE | 0.016 | 0.068 | 1.366 | 0.241 | 0.236 | 0.015 | 65.0 | 0.030 |
| | JULY | 0.000 | -0.005 | 1.169 | 0.262 | 0.269 | 0.025 | 55.0 | 0.043 |
| | AUGUST | 0.003 | 0.002 | 1.155 | 0.257 | 0.269 | 0.025 | 37.0 | 0.031 |
| | SEPT | 0.001 | 0.003 | 1.163 | 0.182 | 0.194 | 0.015 | 38.0 | 0.010 |

Table 8: Cross Validation Results for Region 3, Yearly Data

| | | AKE | $m_{se}$ | $S^2_{se}$ | Standard error | Deviation variable | VARIOGRAM:spherical model NUGGET | RANGE | SILL |
|---|---|---|---|---|---|---|---|---|---|
| 1985 | MAY | 0.095 | 0.100 | 1.097 | 0.475 | 0.574 | 0.000 | 86.0 | 0.327 |
| | JUNE | 0.086 | 0.087 | 0.956 | 0.425 | 0.676 | 0.000 | 116.0 | 0.460 |
| | JULY | 0.059 | 0.083 | 0.971 | 0.345 | 0.493 | 0.000 | 114.0 | 0.264 |
| | AUGUST | 0.072 | 0.094 | 0.873 | 0.355 | 0.507 | 0.000 | 114.0 | 0.329 |
| | SEPT | 0.058 | 0.123 | 1.418 | 0.359 | 0.385 | 0.000 | 107.0 | 0.116 |
| 1986 | MAY | 0.090 | 0.094 | 1.007 | 0.424 | 0.572 | 0.000 | 86.0 | 0.327 |
| | JUNE | 0.073 | 0.077 | 0.977 | 0.363 | 0.670 | 0.000 | 116.0 | 0.460 |
| | JULY | 0.075 | 0.108 | 0.987 | 0.343 | 0.573 | 0.000 | 114.0 | 0.264 |
| | AUGUST | 0.049 | 0.068 | 0.730 | 0.271 | 0.572 | 0.000 | 114.0 | 0.329 |
| | SEPT | 0.057 | 0.117 | 1.087 | 0.263 | 0.369 | 0.000 | 107.0 | 0.116 |
| 1987 | MAY | 0.079 | 0.088 | 0.937 | 0.368 | 0.577 | 0.000 | 86.0 | 0.327 |
| | JUNE | 0.084 | 0.088 | 1.172 | 0.436 | 0.686 | 0.000 | 116.0 | 0.460 |
| | JULY | 0.071 | 0.098 | 1.014 | 0.359 | 0.523 | 0.000 | 114.0 | 0.264 |
| | AUGUST | 0.053 | 0.075 | 0.849 | 0.306 | 0.567 | 0.000 | 114.0 | 0.329 |
| | SEPT | 0.019 | 0.054 | 1.193 | 0.229 | 0.288 | 0.000 | 107.0 | 0.116 |

Table 9: Cross Validation Results for Region 4, Yearly Data

| | | AKE | $m_{se}$ | $S^2_{se}$ | Standard error | Deviation variable | VARIOGRAM:spherical model NUGGET | RANGE | SILL |
|---|---|---|---|---|---|---|---|---|---|
| 1985 | MAY | -0.023 | -0.045 | 1.236 | 0.392 | 0.397 | 0.015 | 100.0 | 0.136 |
| | JUNE | -0.034 | -0.077 | 1.346 | 0.433 | 0.520 | 0.035 | 110.0 | 0.107 |
| | JULY | -0.007 | -0.026 | 1.272 | 0.330 | 0.330 | 0.025 | 57.0 | 0.048 |
| | AUGUST | -0.028 | -0.058 | 1.153 | 0.349 | 0.325 | 0.030 | 110.0 | 0.120 |
| | SEPT | -0.020 | -0.050 | 1.099 | 0.278 | 0.317 | 0.015 | 100.0 | 0.095 |
| 1986 | MAY | -0.019 | -0.038 | 1.027 | 0.305 | 0.349 | 0.015 | 100.0 | 0.136 |
| | JUNE | -0.011 | -0.025 | 1.018 | 0.313 | 0.354 | 0.035 | 110.0 | 0.107 |
| | JULY | -0.012 | -0.039 | 1.163 | 0.308 | 0.280 | 0.025 | 57.0 | 0.048 |
| | AUGUST | -0.010 | -0.017 | 1.049 | 0.312 | 0.323 | 0.030 | 110.0 | 0.120 |
| | SEPT | -0.017 | -0.042 | 0.977 | 0.256 | 0.276 | 0.015 | 100.0 | 0.095 |
| 1987 | MAY | -0.029 | -0.067 | 1.072 | 0.349 | 0.393 | 0.015 | 100.0 | 0.136 |
| | JUNE | -0.034 | -0.081 | 1.197 | 0.397 | 0.501 | 0.035 | 110.0 | 0.107 |
| | JULY | -0.004 | -0.019 | 1.073 | 0.281 | 0.286 | 0.025 | 57.0 | 0.048 |
| | AUGUST | -0.024 | -0.054 | 1.058 | 0.339 | 0.464 | 0.030 | 110.0 | 0.120 |
| | SEPT | -0.007 | -0.022 | 0.923 | 0.234 | 0.267 | 0.015 | 100.0 | 0.095 |

Table 10: Cross Validation Results for Region 5, Yearly Data

| | | | | | Standard | Deviation | VARIOGRAM:spherical model | | |
|---|---|---|---|---|---|---|---|---|---|
| | | AKE | $m_{se}$ | $S^2_{se}$ | error | variable | NUGGET | RANGE | SILL |
| 1985 | MAY | 0.005 | 0.005 | 1.323 | 0.351 | 0.544 | 0.015 | 100.0 | 0.130 |
| | JUNE | -0.001 | -0.010 | 1.391 | 0.391 | 0.621 | 0.015 | 160.0 | 0.270 |
| | JULY | -0.003 | -0.009 | 1.153 | 0.348 | 0.608 | 0.015 | 240.0 | 0.450 |
| | AUGUST | -0.010 | -0.035 | 1.037 | 0.327 | 0.402 | 0.060 | 200.0 | 0.100 |
| | SEPT | -0.002 | -0.012 | 0.913 | 0.275 | 0.336 | 0.060 | 220.0 | 0.080 |
| 1986 | MAY | 0.009 | 0.017 | 0.869 | 0.254 | 0.445 | 0.015 | 100.0 | 0.130 |
| | JUNE | -0.004 | -0.009 | 1.132 | 0.327 | 0.643 | 0.015 | 160.0 | 0.270 |
| | JULY | 0.002 | 0.002 | 1.355 | 0.366 | 0.647 | 0.015 | 240.0 | 0.450 |
| | AUGUST | -0.011 | -0.034 | 1.078 | 0.336 | 0.435 | 0.060 | 200.0 | 0.100 |
| | SEPT | -0.003 | -0.009 | 0.754 | 0.226 | 0.353 | 0.060 | 220.0 | 0.080 |
| 1987 | MAY | -0.003 | -0.014 | 1.253 | 0.336 | 0.518 | 0.015 | 100.0 | 0.130 |
| | JUNE | -0.001 | -0.003 | 1.046 | 0.306 | 0.555 | 0.015 | 160.0 | 0.270 |
| | JULY | -0.008 | -0.010 | 1.019 | 0.309 | 0.631 | 0.015 | 240.0 | 0.450 |
| | AUGUST | -0.012 | -0.041 | 1.029 | 0.328 | 0.416 | 0.060 | 200.0 | 0.100 |
| | SEPT | -0.005 | -0.019 | 1.025 | 0.313 | 0.362 | 0.060 | 220.0 | 0.080 |

## 5.5 CONTOUR MAPS OF KRIGED ETr AND STANDARD DEVIATIONS FOR REGIONS

The averaged ETr estimates during July and September for regions 1, 2, 4, and 5 were used in the kriging analysis. Kriging was performed to estimate reference evapotranspiration over a grid superimposed on the region. The grid size was on a 10 km by 10 km interval. Using the model variogram validated for those months and regions along with the observed ETr estimates, the KRIGE routine in Geo-EAS estimated ETr and the standard deviation at the unknown grid points applying the kriging analysis discussed in the Literature Review. SURFER was used to produce the contour maps for the regions during July and September. Figures 18 through 33 are contour maps of kriged ETr estimates and the error associated with the kriged estimates plotted from the SURFER software package.

In general, the maps within each region displayed a consistent shape of contours for ETr and the standard deviation of the kriging error between July and September. As expected, the contour maps show a higher rate of ETr for the middle of the growing season (July) compared to the end of the season (September). This trend agreed with that seen in Fig. 8. The contour interval was set at the minimum standard deviation of the error for the region. In practice, the contour interval is usually two times the standard deviation. However, if this contour interval had been applied, only one contour would be plotted for most regions and not enough information about the shape of the contour would be given. This result strongly suggests that the regions used in the analysis are homogeneous. A problem occurred in region 1 due to the extreme ratio of length to width. To show contour lines for this region, the X and Y scale were manipulated so that one X unit was equal to two Y units.

It was noticed that the values of ETr of individual meteorological stations within the regions influenced the shape of the contour lines and the shpae did not necessarily correspond to topographic effects in Oregon. In region 1, the contour lines did not follow a north to south orientation as expected from to the topographic and vegetation influence of the Coastal range. One explanation is that the weather stations used for the ETr estimates are generally representative of the valleys in each region. For use in hydrologic modeling or irrigation system design and scheduling in regional valleys, the kriged ETr estimates could be very satisfactory. However, for use in large scale hydrologic modeling or global circulation models, a method to account for the topographic and vegetation effects must be included in the kriged ETr estimates.

Comparing contours between regions was difficult because the contour lines were not always able to be set to the same contour interval. To effectively utilize these contour maps within regions for the whole state, there must be some method to deal with the transition zones between regions. A possibility is to combine kriged estimates from each region into one file representing the whole state and produce contour plots from the overall data file.

The contour maps for standard deviations of the kriged estimates show the distribution of the errors over the region. The standard deviation was generally uniform over a region. Typically, there was a low standard deviation for a homogeneous region with a high number of sample locations (weather stations). Since the individual regions were already assumed homogeneous (stationarity), the standard deviations depended mainly on the station density. Therefore, the interest in these contour maps of standard deviations is in identifying locations where additional weather stations could be placed thereby reducing the error of the estimate and improving the ETr estimates. Looking at region 5, the lower right corner of the region had the highest standard deviations which suggests a lack of stations to represent that area.

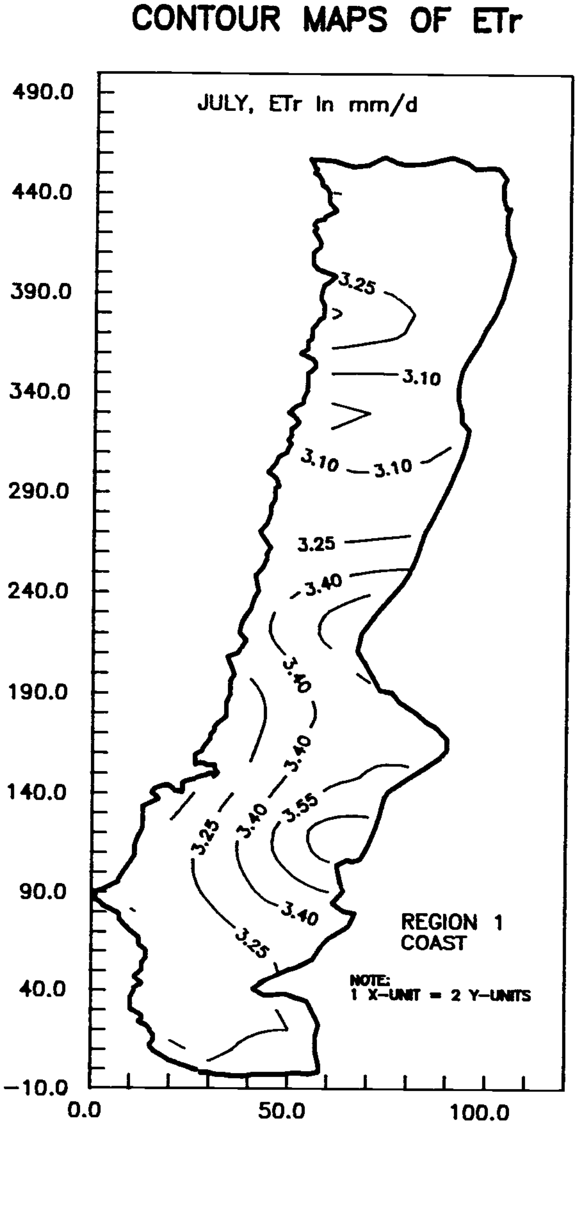



Figure 18: Contour Map of Kriged ETr estimates for July in Region 1

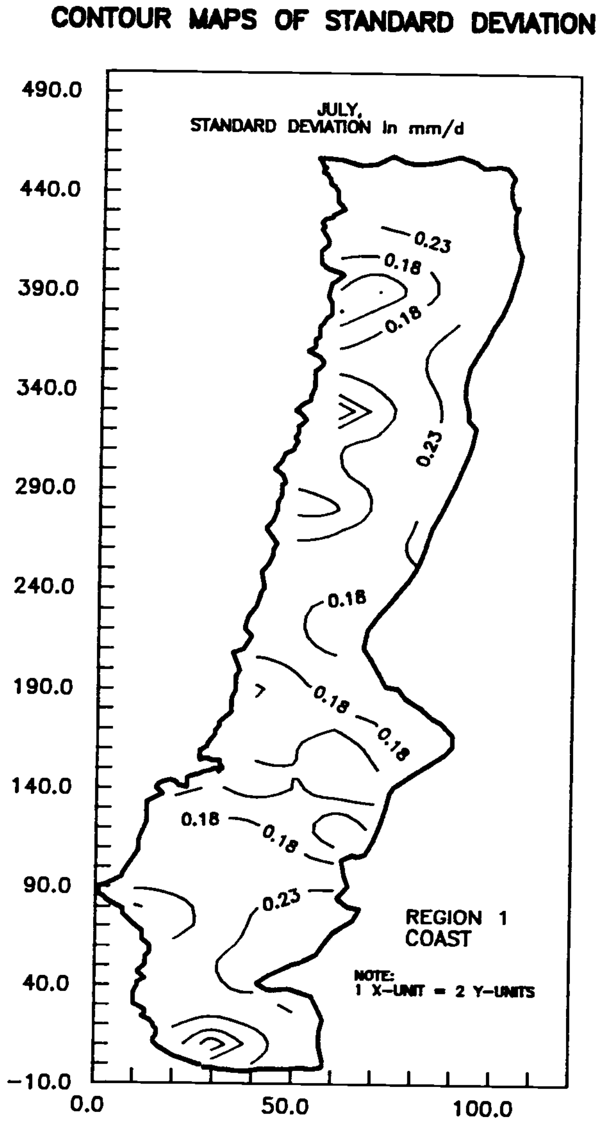



Figure 19: Contour Map of Kriged Standard Deviations for July in Region 1

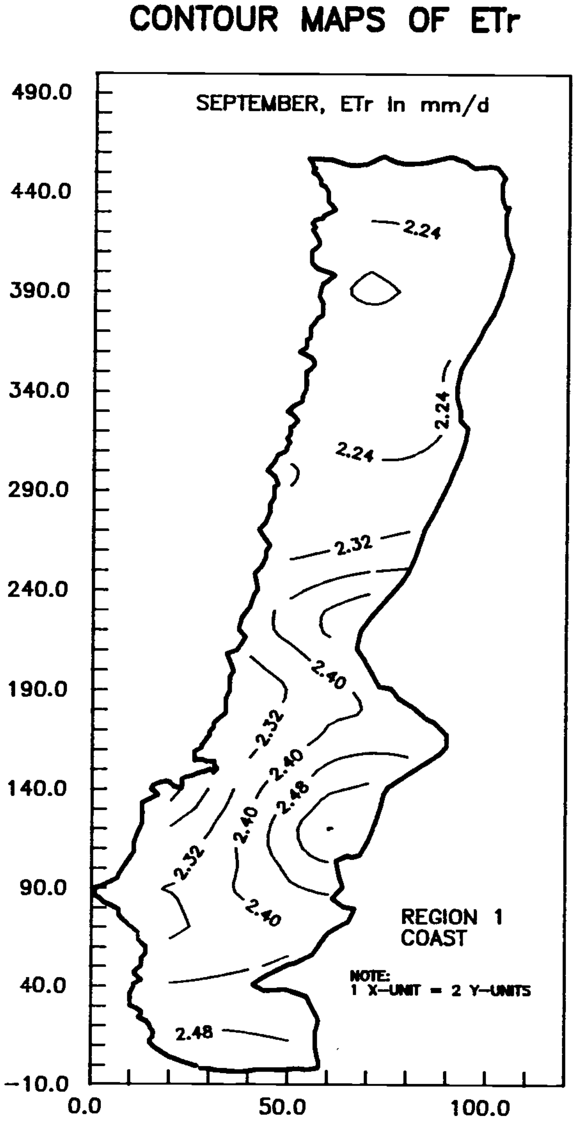



Figure 20: Contour Map of Kriged ETr estimates for Sept. in Region 1

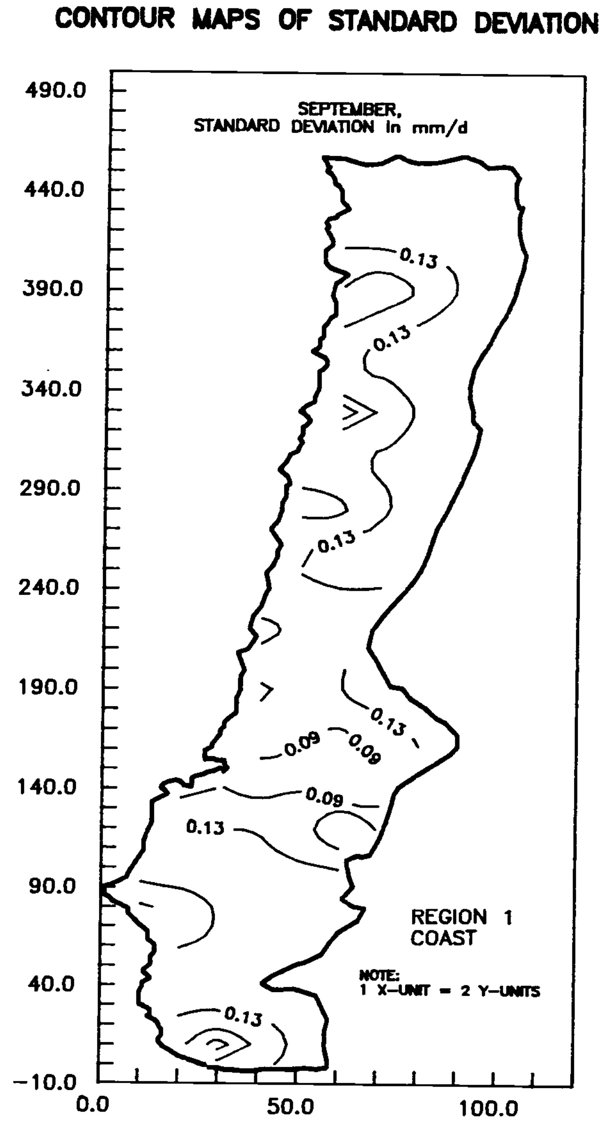



Figure 21: Contour Map of Kriged Standard Deviations for Sept. in Region 1

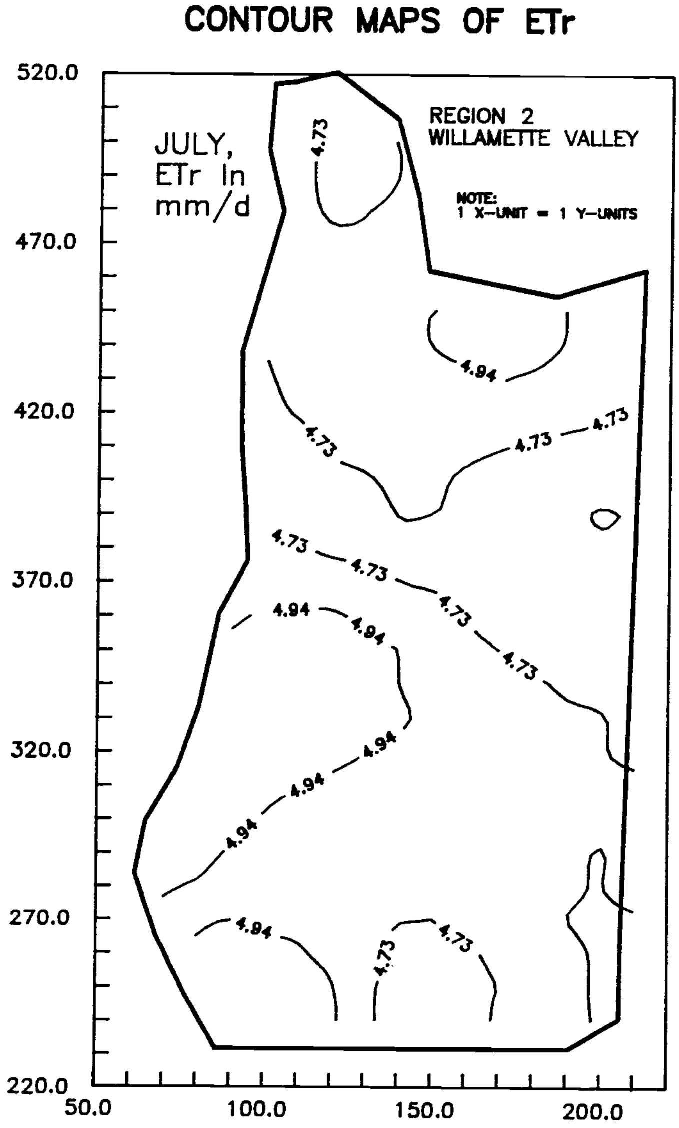



Figure 22: Contour Map of Kriged ETr estimates for July in Region 2

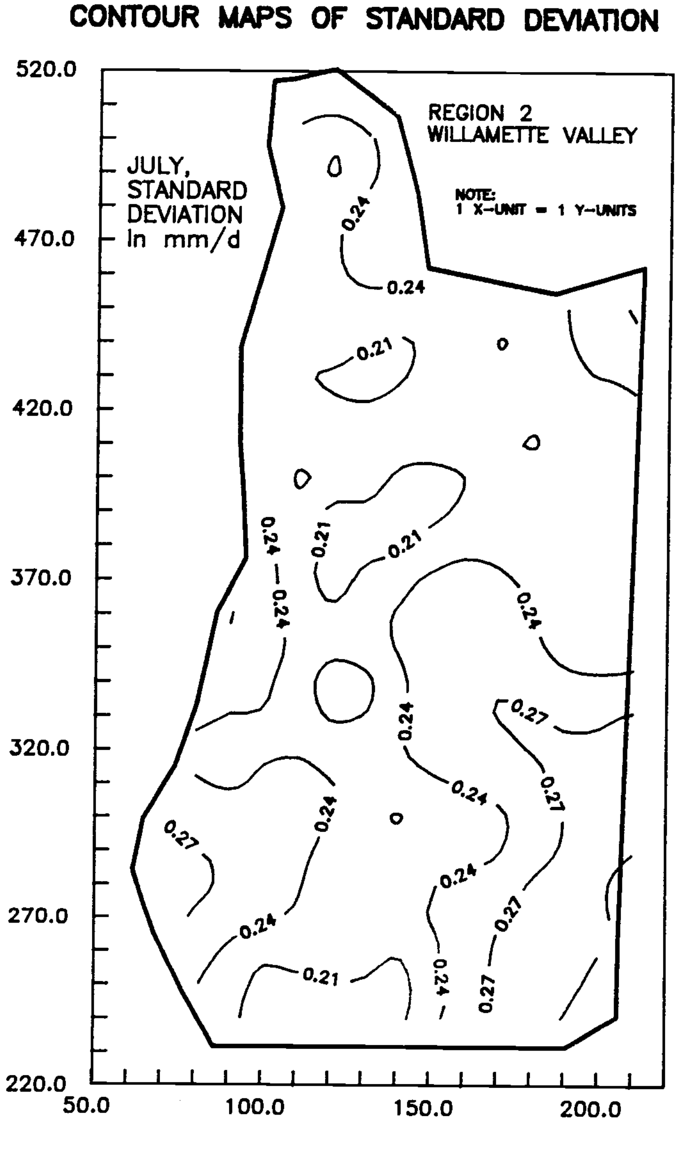



Figure 23: Contour Map of Kriged Standard Deviations for July in Region 2

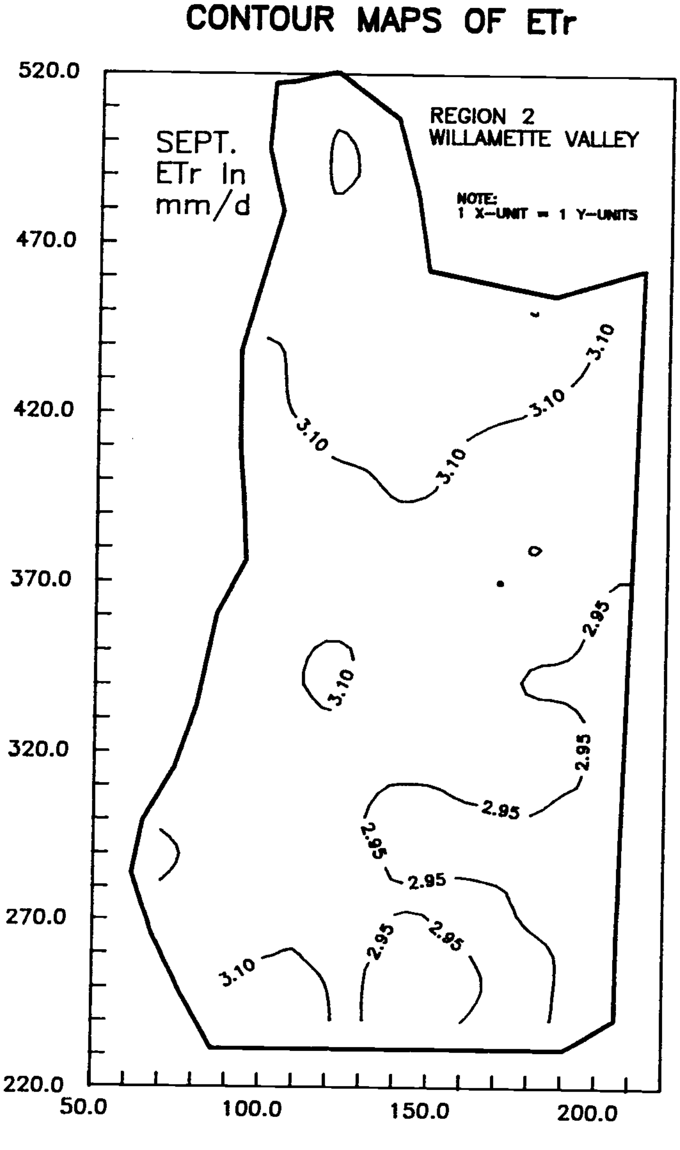



Figure 24: Contour Map of Kriged ETr estimates for Sept. in Region 2

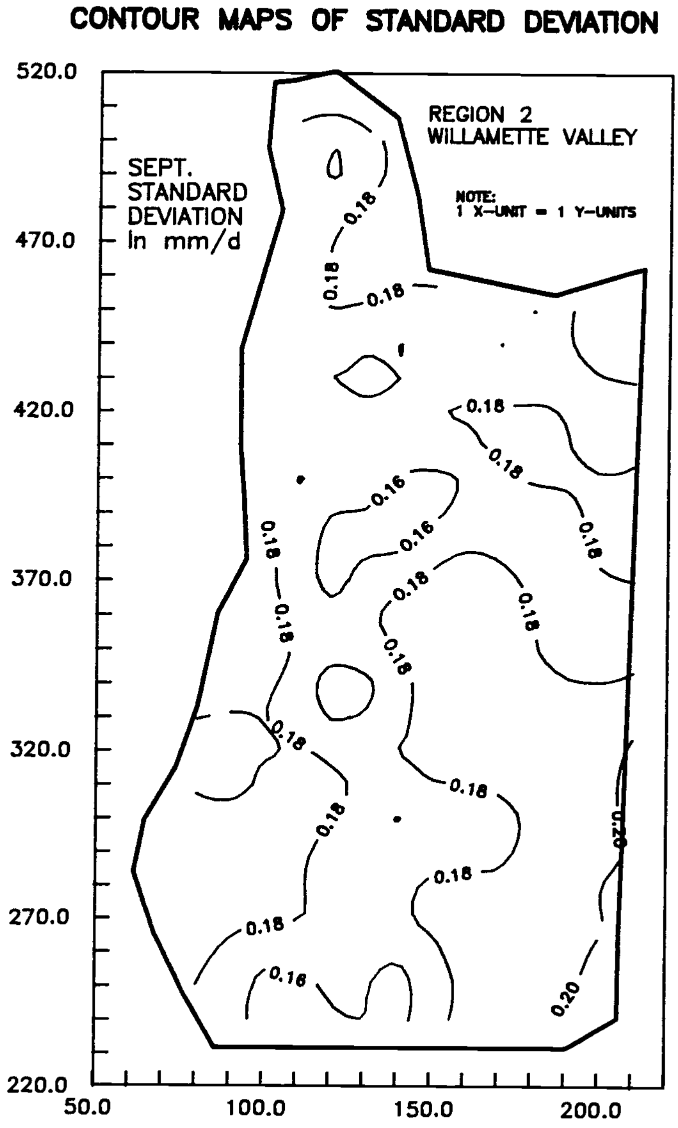



Figure 25: Contour Map of Kriged Standard Deviations for Sept. in Region 2

# CONTOUR MAPS OF ETr

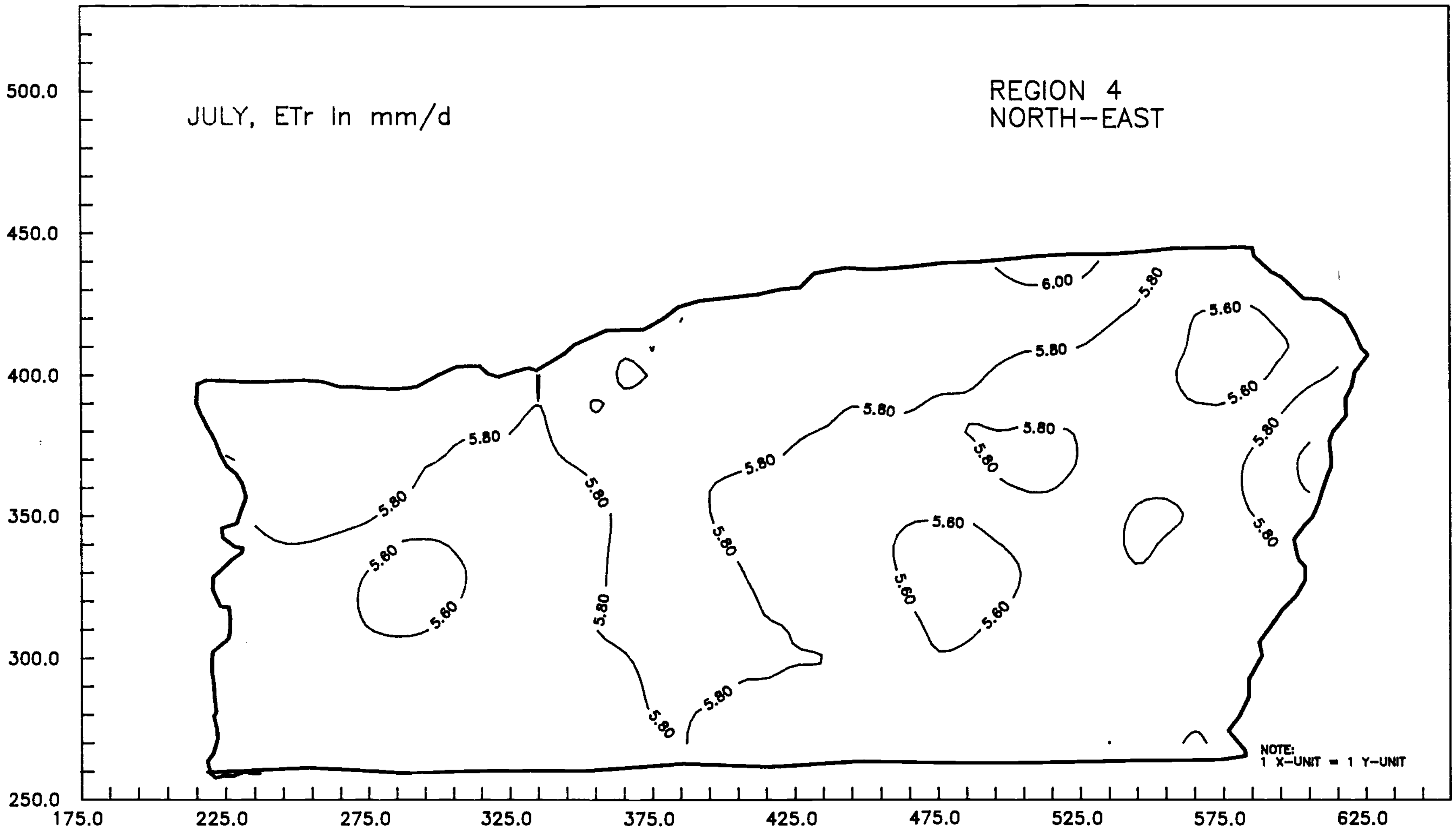



Figure 26: Contour Map of Kriged ETr estimates for July in Region 4

## CONTOUR MAPS OF STANDARD DEVIATION

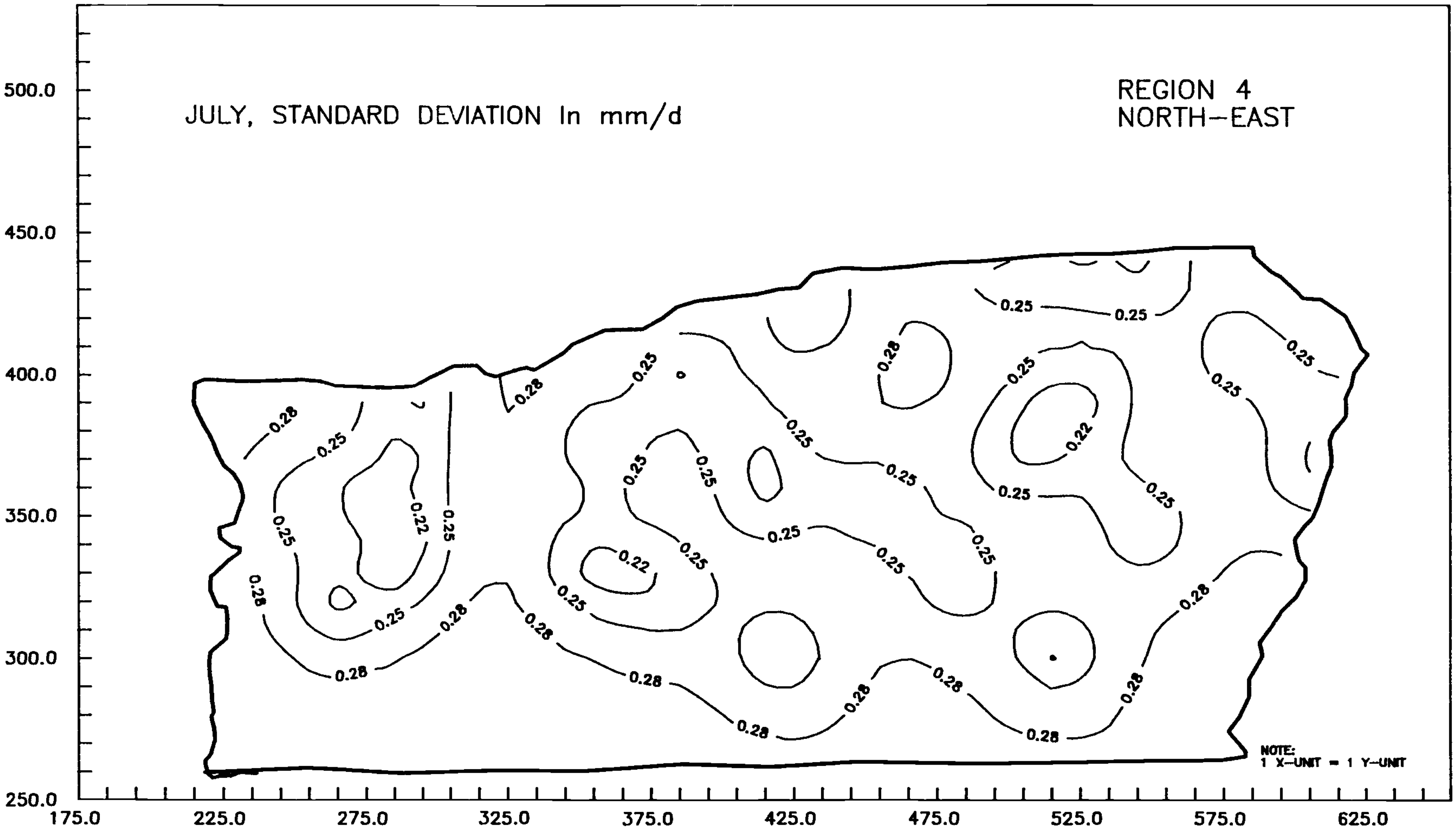



Figure 27: Contour Map of Kriged Standard Deviations for July in Region 4

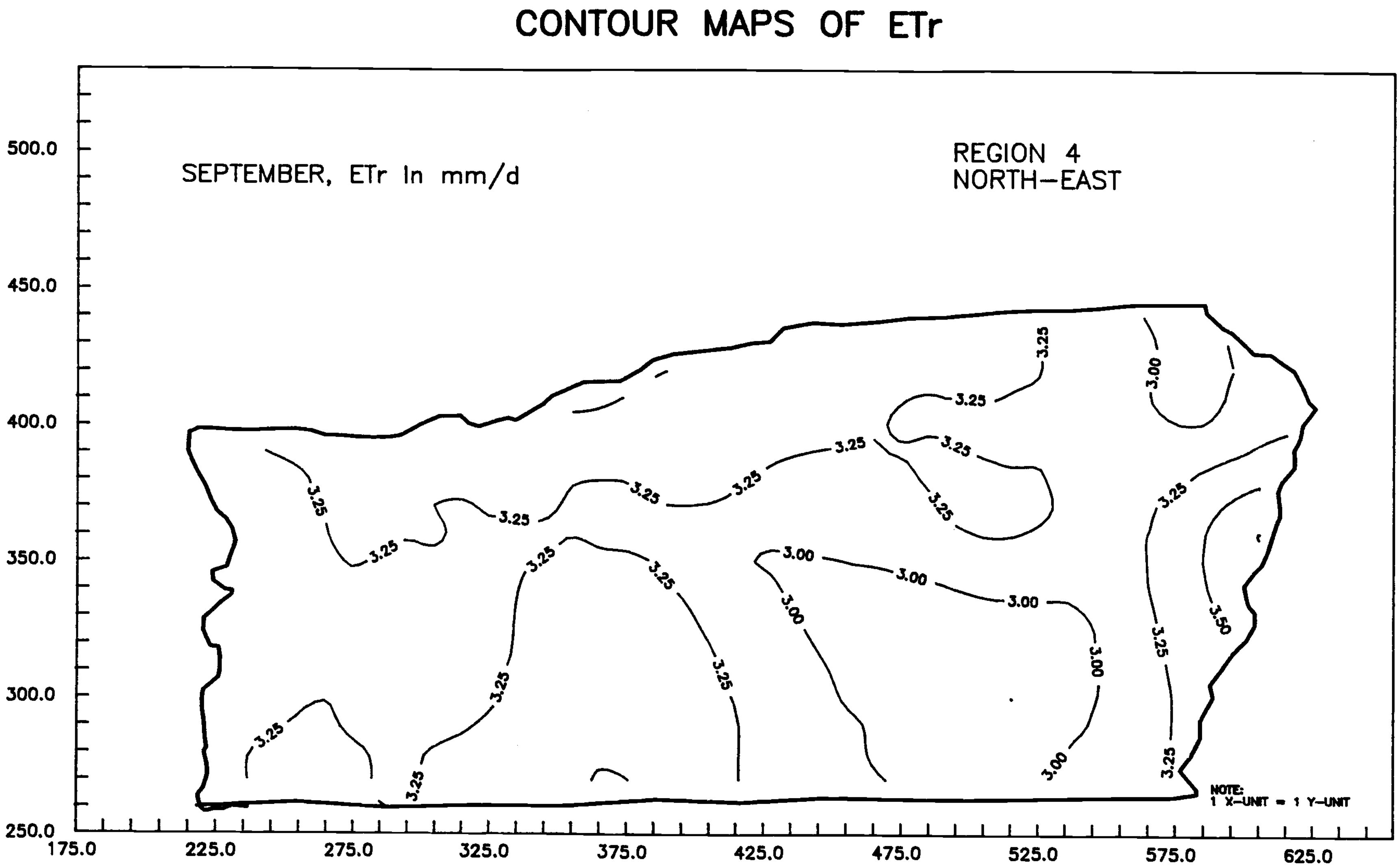



Figure 28: Contour Map of Kriged ETr estimates for Sept. in Region 4

# CONTOUR MAPS OF STANDARD DEVIATION

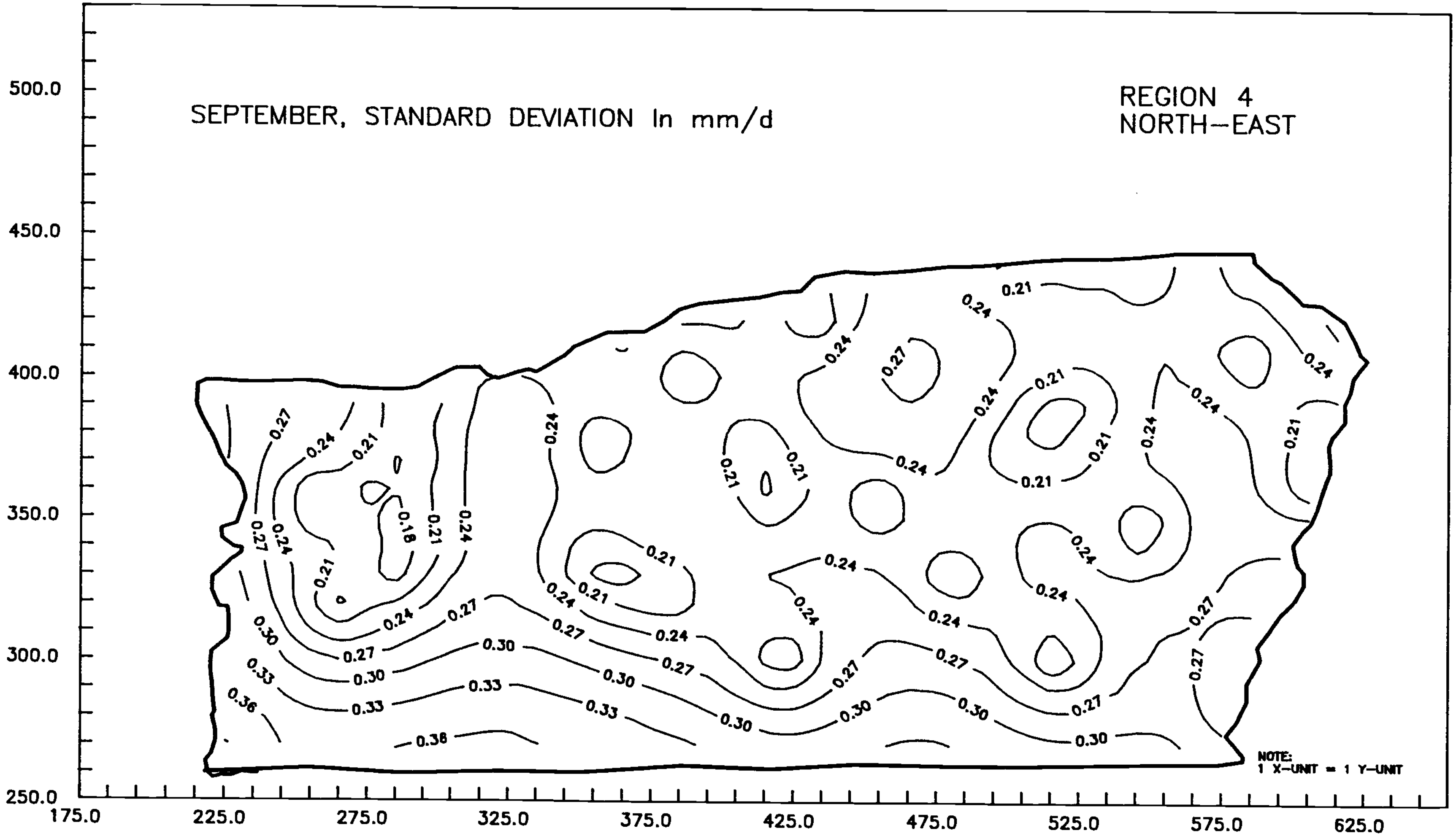



Figure 29: Contour Map of Kriged Standard Deviations for Sept. in Region 4

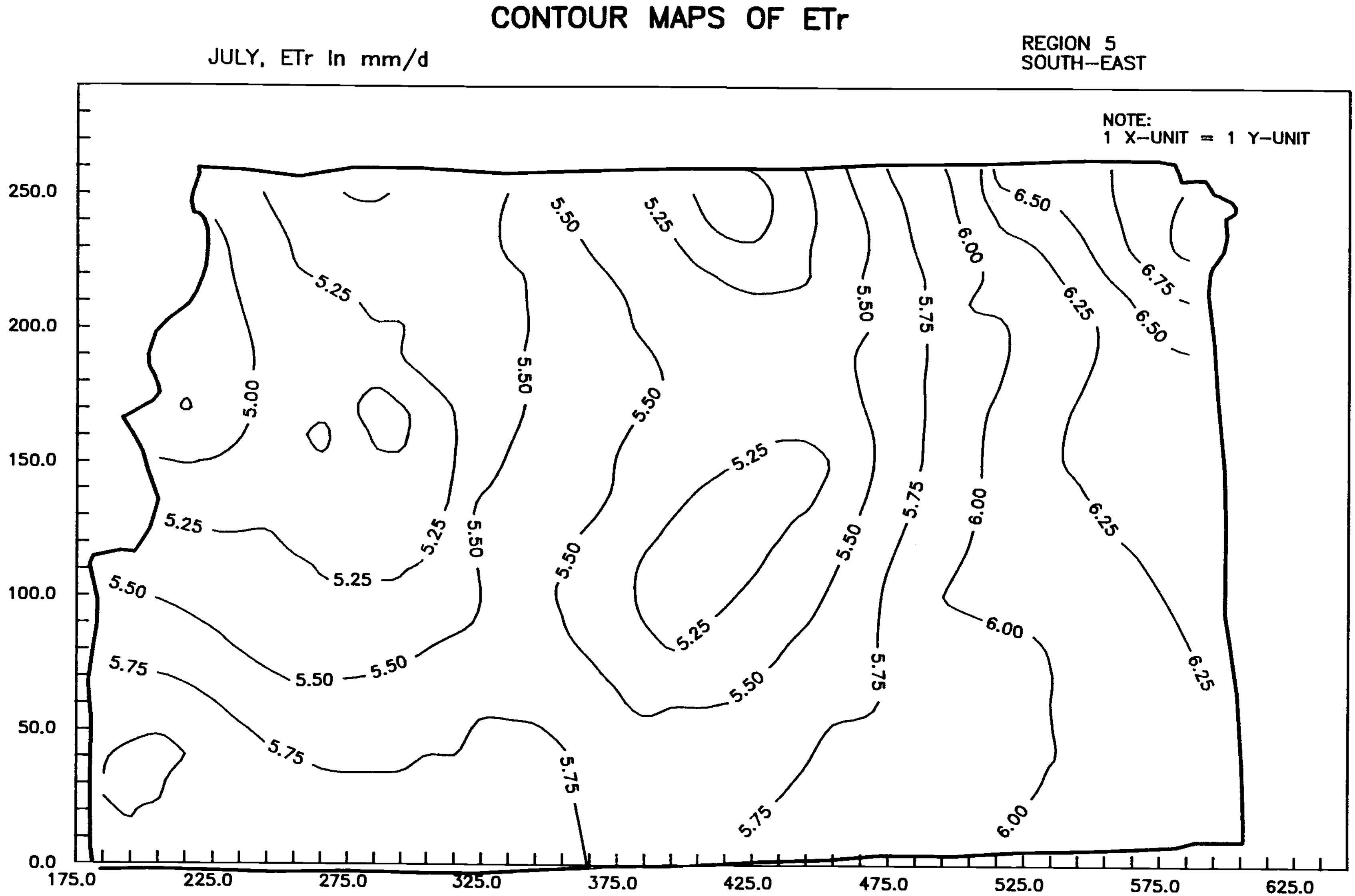



Figure 30: Contour Map of Kriged ETr estimates for July in Region 5

## CONTOUR MAPS OF STANDARD DEVIATION

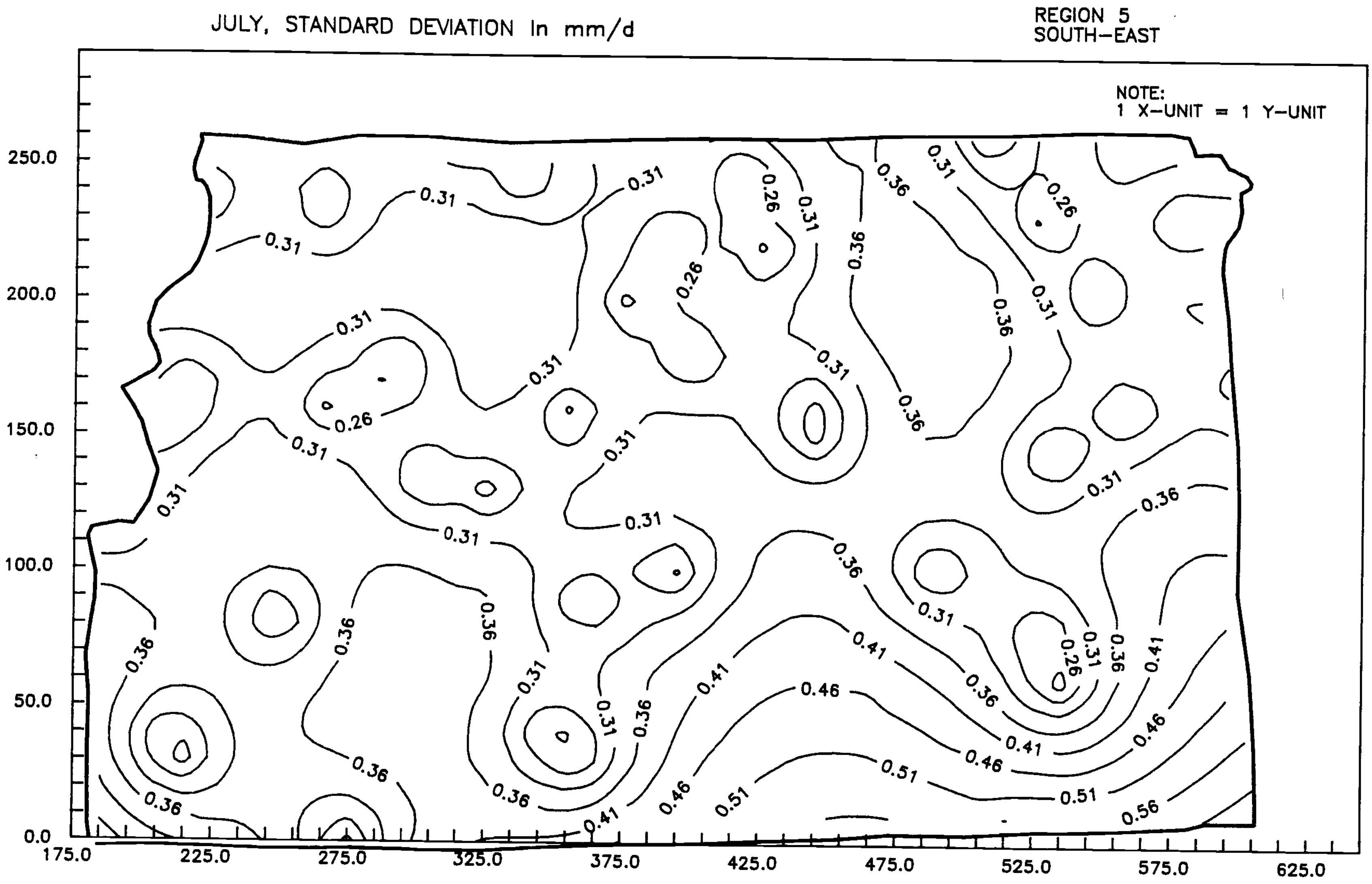



Figure 31: Contour Map of Kriged Standard Deviations for July in Region 5

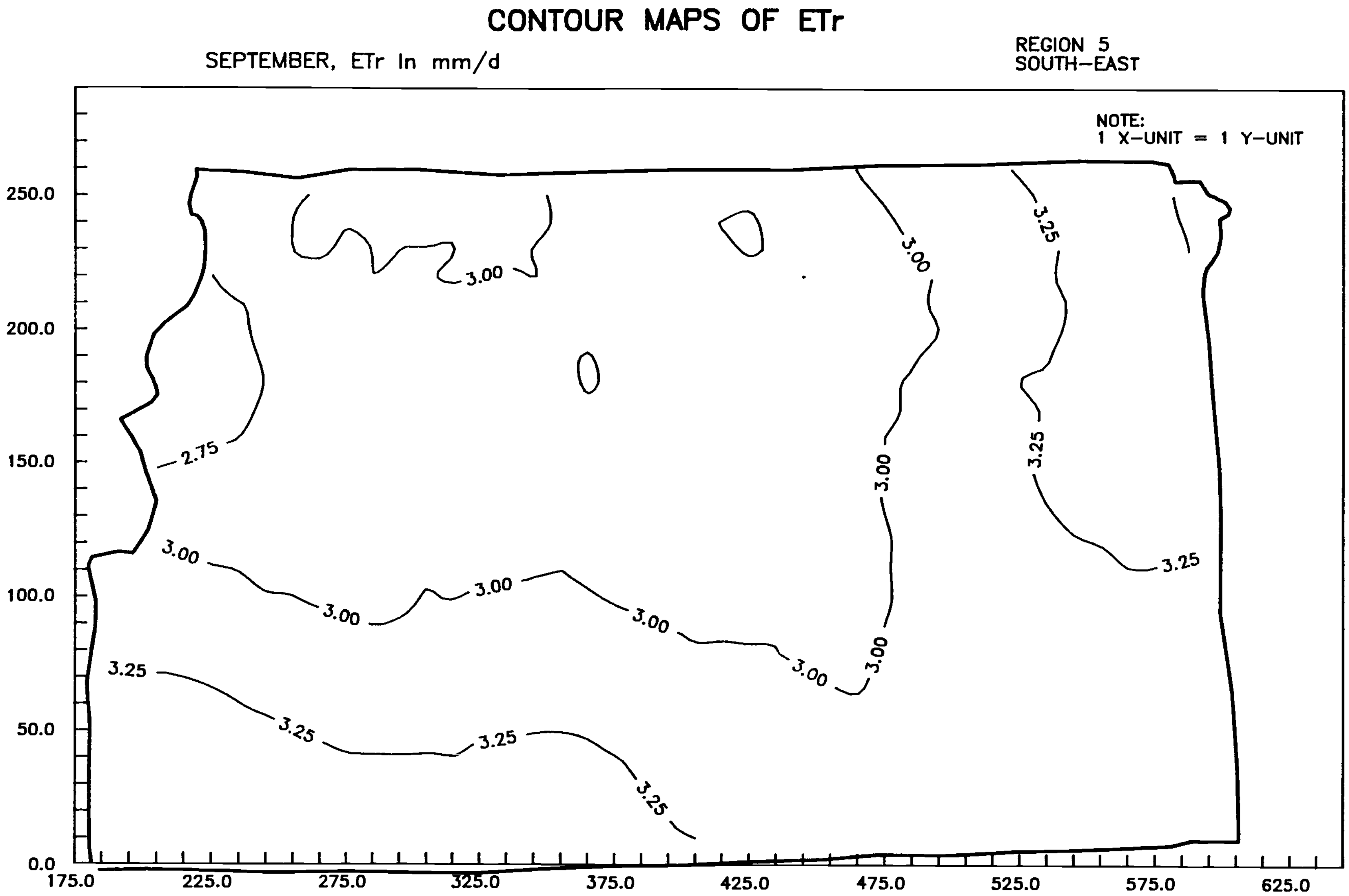



Figure 32: Contour Map of Kriged ETr estimates for Sept. in Region 5

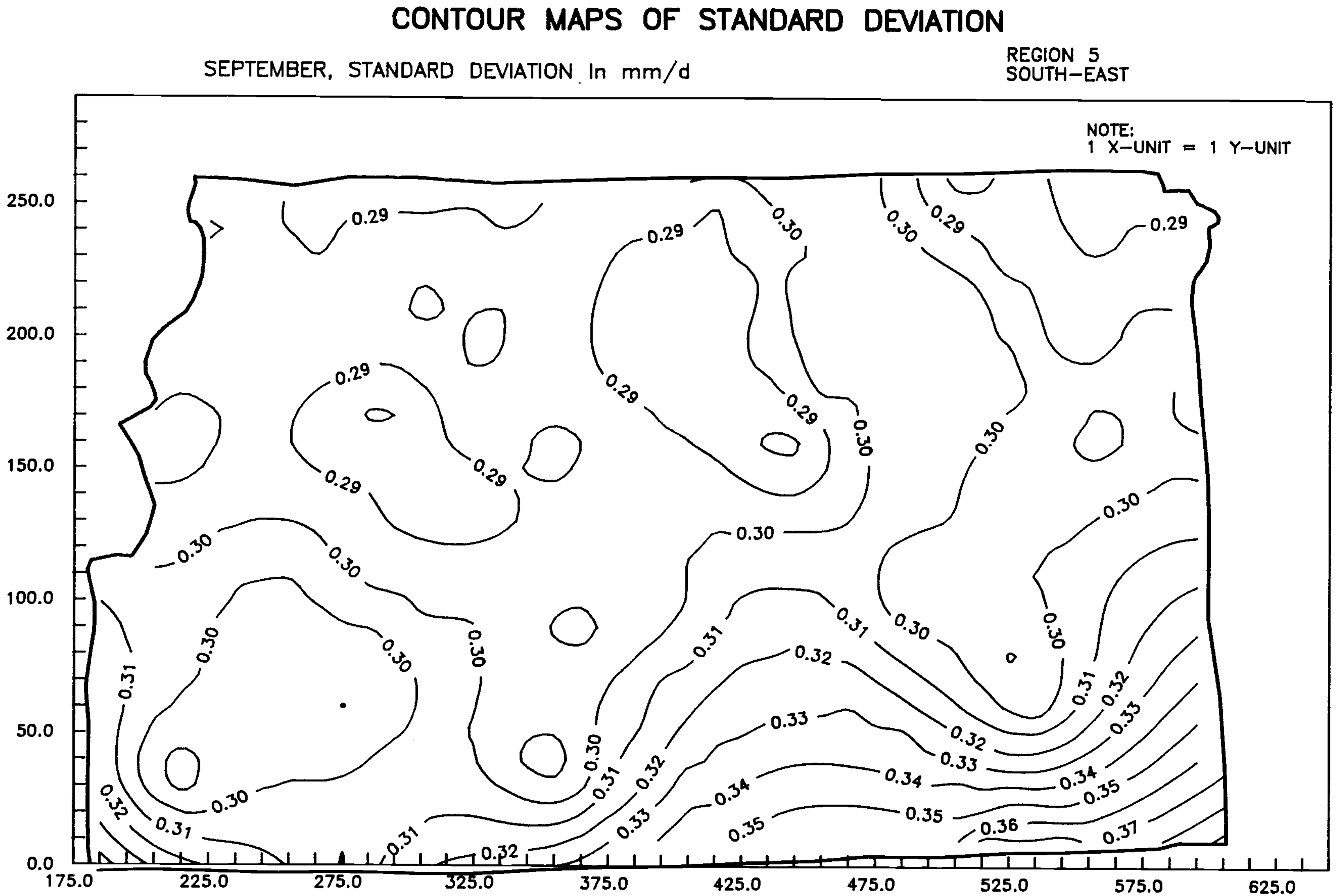



Figure 33: Contour Map of Kriged Standard Deviations for Sept. in Region 5

# 6 CONCLUSIONS AND RECOMMENDATIONS

The FAO-modified Blaney-Criddle method was used to compute local estimates of monthly reference evapotranspiration, ETr, for 180 weather stations over the state of Oregon during 1985, 1986, and 1987. This method was selected over other local estimating methods because previous research in states adjacent to Oregon indicated this to be the most accurate temperature-based method. In addition, since this method relies predominantly on temperature, it was found to be compatible with the weather data available throughout Oregon.

The state was divided into five climatic regions based on topographic features and local meteorological conditions: 1) Coast, 2) Willamette Valley, 3) Southwestern Valley, 4) North East, and 5) South East. The ETr estimates were allocated to their respective regions and averaged over the three years. The average ETr estimates were used to compute sample variograms for each month from May through September in each region. Model variograms were fitted to the sample variograms using the spherical model and validated through a cross validation procedure. For four out of the five regions, a verified spherical model was obtained for the individual months. It was difficult to confirm that the model variograms for region 3 were valid because the values for AKE and the mean standardized error ($m_{\bullet\bullet}$) diverged more from zero when compared to the other regions. The small number of ETr estimates in this region contributed to the fact that model variograms were not able to be verified.

Amegee (1985) commented on the problem of using all data available on a large heterogeneous region to compute the sample variograms compared to computing the sample variograms for separate climatic regions within the larger geographic region. The strength of subregional analysis is that the stationarity assumptions are better sustained. However, the limited number of samples available within the region makes it more difficult to successfully fit a model variogram to the data. This was particularly the case in region 3. The state of Oregon was divided into 5 climatic regions. A closer look at the data in each region might provide justification for combining certain regions together. Regions might be able to be combined resulting in more ETr estimates to characterize spatial variation without jeopardizing the stationary assumptions required for geostatistics.

The model variograms determined for the average ETr estimates were used as the variograms for the individual years (1985, 1986, and 1987) to test the hypothesis that one model variogram could represent the spatial correlation of ETr for the region. From the cross validation results, no valid conclusions to support this hypothesis could be made due to the inconsistency seen in the success and failure rate of applying the model variograms for the average ETr data to the individual years. It is recommended to develop the model variograms from long term average ETr estimates which could provide better results when applied to individual years.

Kriging was performed on the average ETr estimates for July and September in regions 1, 2, 4, and 5. Using the validated model variograms for these months and regions along with the observed ETr estimates, the kriging analysis was used to estimated the ETr and standard deviation of the error over a grid representing the region. The grid interval was 10 km by 10 km. In general, the maps within each region displayed a consistent shape of contours for ETr and the standard deviation of the kriging error between the months. The contours of standard deviation of the kriging error also agreed with the weather station densities within the regions and were generally uniform over a region. The knowledge of the standard deviation of the kriging errors could assist in identifying locations where additional weather stations could be placed thereby reducing the error of the estimate and improving the ETr estimates.

In practice, the contour interval is often two times the standard deviation. However, in this project, the contour interval was set at the minimum standard deviation of the error for the region. This contour interval had to be applied because only one contour could be plotted for most regions if the interval was set at twice the standard deviation. This fact strongly suggests that the regions used in the analysis are homogeneous.

It was noticed that the values of ETr of individual meteorological stations within the regions influenced the shape of the contour lines and the shape did not necessarily correspond to topographic effects in Oregon. This was particularly seen in region 1 where the contour lines did not follow a north to south orientation as expected. One explanation is that the weather stations used for the ETr estimates are generally representative of the valleys in each region. For use in hydrologic modeling or irrigation system design and scheduling in regional valleys, the kriged ETr estimates could be very satisfactory. However, for use in large scale hydrologic modeling or global circulation models, a method to account for the topographic effects must be included in the kriged ETr estimates. A method that might prove successful is developing a spatial correlation between ETr and elevation through a geostatistical technique termed cokriging.

Another problem with the regional analysis was comparison at regional boundaries. It was difficult to compare contours across climatic regions because the contour lines were not coincident. To effectively utilize these contour maps for the whole state, there must be some method to deal with the transition zones between regions. A possibility is to combine kriged estimates from each region into one file representing the whole state and producing contour plots for the overall data file.

It is not difficult to see the usefulness of computerized plots of reference evapotranspiration in water resources management. Geostatistics is one possible tool to generate these estimates and plots. There are indeed difficults to overcome for geostatistics to be applied operationally in estimating regional evapotranspiration. However, the use of geostatistics is becoming more common in hydrology and its use is expected to grow.

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# APPENDICES

# APPENDIX A: Primary Weather Data

List of the stations included in this study with information about their location, latitude, longitude and site, area, region and cumulative aridities.

| R | STN | Station name | Lat (deg) | Long (deg) | Elev (m) | Aridity (%) S | A | R | C |
|---|---|---|---|---|---|---|---|---|---|
| 5 | 0036 | Adel | 42.18 | 119.90 | 1396 | 100 | 80 | 100 | 90 |
| 5 | 0118 | Alkali Lake | 42.97 | 120.00 | 1320 | 100 | 50 | 80 | 73 |
| 5 | 0189 | Andrews Weston Mine | 42.55 | 118.55 | 1457 | 100 | 100 | 100 | 100 |
| 4 | 0197 | Antelope | 44.92 | 120.72 | 817 | 100 | 50 | 50 | 70 |
| 4 | 0265 | Arlington | 45.72 | 120.20 | 88 | 30 | 50 | 30 | 40 |
| 3 | 0304 | Ashland | 42.22 | 122.72 | 543 | 30 | 50 | 50 | 42 |
| 1 | 0328 | Astoria Airport | 46.15 | 123.88 | 3 | 30 | 30 | 0 | 27 |
| 4 | 0356 | Austin | 44.58 | 118.50 | 1283 | 30 | 30 | 20 | 29 |
| 4 | 0412 | Baker Airport | 44.83 | 117.82 | 1027 | 30 | 10 | 20 | 19 |
| 1 | 0471 | Bandon | 43.15 | 124.40 | 6 | 90 | 10 | 10 | 42 |
| 5 | 0501 | Barnes Station | 43.95 | 120.22 | 1210 | 90 | 80 | 80 | 84 |
| 2 | 0595 | Beaverton | 45.50 | 122.82 | 67 | 30 | 20 | 20 | 24 |
| 5 | 0694 | Bend | 44.07 | 121.32 | 1113 | 70 | 70 | 90 | 72 |
| 5 | 0723 | Beulah | 43.92 | 118.17 | 997 | 10 | 50 | 90 | 38 |
| 4 | 0858 | Boardman | 45.83 | 119.70 | 91 | 10 | 20 | 20 | 16 |
| 2 | 0897 | Bonneville Dam | 45.63 | 121.95 | 18 | 10 | 10 | 10 | 10 |
| 1 | 1055 | Brookings | 42.05 | 124.28 | 21 | 10 | 10 | 0 | 9 |
| 5 | 1067 | Brothers | 43.80 | 120.60 | 1414 | 90 | 90 | 90 | 90 |
| 5 | 1174 | Burns Junction | 42.78 | 117.85 | 1198 | 90 | 100 | 100 | 96 |
| 5 | 1175 | Burns Airport | 43.58 | 118.95 | 1262 | 70 | 70 | 80 | 71 |
| 2 | 1433 | Cascadia | 44.40 | 122.48 | 262 | 0 | 0 | 0 | 0 |
| 3 | 1448 | Cave Junction | 42.17 | 123.67 | 390 | 10 | 30 | 30 | 22 |
| 5 | 1546 | Chemult | 43.23 | 121.78 | 1451 | 80 | 60 | 60 | 68 |
| 5 | 1574 | Chiloquin | 42.65 | 121.95 | 1268 | 10 | 50 | 50 | 34 |
| 2 | 1643 | Clatskanie | 46.10 | 123.28 | 27 | 10 | 0 | 0 | 4 |
| 1 | 1682 | Cloverdale | 45.22 | 123.90 | 24 | 10 | 10 | 10 | 10 |
| 4 | 1765 | Condon | 45.23 | 120.18 | 863 | 10 | 70 | 80 | 47 |
| 1 | 1836 | Coquille City | 43.18 | 124.20 | 6 | 10 | 10 | 10 | 10 |
| 2 | 1862 | Corvallis OSU | 44.63 | 123.20 | 70 | 10 | 10 | 10 | 10 |
| 2 | 1877 | Corvallis Water Bureau | 44.52 | 123.45 | 180 | 10 | 10 | 10 | 10 |
| 2 | 1897 | Cottage Grove | 43.78 | 123.07 | 198 | 10 | 20 | 20 | 16 |
| 2 | 1902 | Cottage Grove Dam | 43.72 | 123.05 | 253 | 90 | 20 | 20 | 48 |

| R | STN | Station name | Lat (deg) | Long (deg) | Elev (m) | Aridity (%) S | A | R | C |
|---|---|---|---|---|---|---|---|---|---|
| 4 | 1924 | Cove | 45.30 | 117.80 | 890 | 90 | 20 | 10 | 47 |
| 5 | 1946 | Crater Lake | 42.90 | 122.13 | 1975 | 50 | 20 | 10 | 17 |
| 2 | 2112 | Dallas | 44.95 | 123.28 | 88 | 80 | 20 | 30 | 45 |
| 5 | 2135 | Danner | 42.93 | 117.33 | 1289 | 80 | 60 | 60 | 68 |
| 4 | 2173 | Dayville | 44.55 | 119.65 | 689 | 80 | 80 | 70 | 79 |
| 2 | 2292 | Detroit Dam | 44.72 | 122.25 | 372 | 80 | 30 | 20 | 49 |
| 1 | 2370 | Dora | 43.17 | 124.00 | 274 | 20 | 30 | 20 | 25 |
| 2 | 2374 | Dorena Dam | 43.78 | 122.97 | 250 | 20 | 40 | 20 | 30 |
| 2 | 2406 | Drain | 43.67 | 123.32 | 88 | 20 | 40 | 30 | 31 |
| 5 | 2415 | Drewsey | 43.80 | 118.38 | 1073 | 80 | 40 | 30 | 55 |
| 4 | 2440 | Dufur | 45.45 | 121.13 | 405 | 80 | 30 | 20 | 49 |
| 4 | 2597 | Elgin | 45.57 | 117.92 | 811 | 20 | 20 | 20 | 20 |
| 1 | 2633 | Elkton | 43.60 | 123.58 | 37 | 20 | 30 | 20 | 25 |
| 4 | 2675 | Enterprise 2 | 45.40 | 117.27 | 1183 | 20 | 30 | 20 | 30 |
| 4 | 2678 | Enterprise 20 | 45.70 | 117.15 | 1000 | 20 | 40 | 20 | 30 |
| 2 | 2693 | Estacada | 45.27 | 122.32 | 125 | 80 | 40 | 30 | 55 |
| 2 | 2709 | Eugene Airport | 44.12 | 123.22 | 110 | 10 | 10 | 10 | 10 |
| 1 | 2805 | Falls City | 44.85 | 123.43 | 134 | 10 | 40 | 30 | 27 |
| 2 | 2867 | Fernridge Dam | 44.12 | 123.30 | 149 | 80 | 10 | 10 | 38 |
| 2 | 2997 | Forest Grove | 45.53 | 123.10 | 55 | 20 | 40 | 30 | 31 |
| 4 | 3038 | Fossil | 45.00 | 120.22 | 808 | 20 | 40 | 30 | 31 |
| 2 | 3047 | Foster Dam | 44.42 | 122.67 | 168 | 80 | 40 | 30 | 55 |
| 5 | 3095 | Fremont | 43.33 | 121.17 | 1375 | 80 | 50 | 60 | 63 |
| 1 | 3193 | Gardiner | 43.73 | 124.30 | 5 | 10 | 10 | 10 | 10 |
| 1 | 3356 | Gold Beach Ranger Stn. | 42.40 | 124.42 | 15 | 20 | 30 | 20 | 25 |
| 2 | 3402 | Government Camp | 45.30 | 121.75 | 1213 | 20 | 10 | 10 | 14 |
| 3 | 3445 | Grants Pass | 42.43 | 123.32 | 283 | 80 | 50 | 60 | 63 |
| 4 | 3542 | Grizzly | 44.52 | 120.93 | 1109 | 20 | 30 | 20 | 25 |
| 4 | 3604 | Halfway | 44.88 | 117.12 | 814 | 20 | 40 | 30 | 31 |
| 5 | 3692 | Hart Mountain Ref. | 42.55 | 119.65 | 1713 | 80 | 80 | 70 | 79 |
| 2 | 3770 | Hwks Portland Wtr. Bu. | 45.45 | 122.15 | 229 | 90 | 10 | 40 | 45 |
| 4 | 3827 | Heppner | 45.37 | 119.55 | 576 | 80 | 90 | 80 | 85 |
| 4 | 3847 | Hermiston | 45.82 | 119.28 | 189 | 10 | 40 | 30 | 27 |
| 2 | 3908 | Hillsboro | 45.52 | 122.98 | 49 | 80 | 30 | 20 | 49 |
| 1 | 3995 | Honeyman State Park | 43.93 | 124.10 | 37 | 20 | 20 | 20 | 20 |
| 4 | 4003 | Hood River Exp. Stn. | 45.68 | 121.52 | 152 | 70 | 20 | 30 | 41 |
| 3 | 4060 | Howard Prairie Dam | 42.22 | 122.37 | 1393 | 80 | 20 | 30 | 45 |
| 4 | 4098 | Huntington | 44.35 | 117.27 | 649 | 80 | 60 | 70 | 69 |
| 3 | 4126 | Idleyld Park | 43.37 | 122.97 | 329 | 20 | 40 | 30 | 31 |
| 1 | 4133 | Illahe | 42.63 | 124.05 | 107 | 20 | 30 | 20 | 25 |
| 5 | 4175 | Ironside | 44.32 | 117.98 | 1195 | 20 | 40 | 30 | 31 |
| 4 | 4291 | John Day | 44.43 | 118.95 | 933 | 80 | 40 | 30 | 55 |
| 5 | 4357 | Juntura | 43.80 | 117.93 | 863 | 70 | 60 | 50 | 63 |
| 4 | 4411 | Kent | 45.20 | 120.70 | 829 | 60 | 70 | 60 | 65 |
| 5 | 4506 | Klamath Falls | 42.20 | 121.78 | 1250 | 50 | 60 | 50 | 55 |
| 5 | 4511 | Klamath Falls Agr. Stn. | 42.17 | 121.75 | 1247 | 70 | 60 | 50 | 63 |

| R | STN | Station name | Lat (deg) | Long (deg) | Elev (m) | Aridity (%) S | A | R | C |
|---|---|---|---|---|---|---|---|---|---|
| 2 | 4606 | La Comb | 44.62 | 122.72 | 158 | 20 | 50 | 40 | 37 |
| 4 | 4622 | La Grande KTVR | 45.32 | 118.08 | 841 | 50 | 40 | 30 | 43 |
| 5 | 4670 | Lakeview | 42.22 | 120.37 | 1457 | 60 | 80 | 100 | 74 |
| 1 | 4776 | Laurel Mountain | 44.92 | 123.57 | 1094 | 80 | 0 | 10 | 33 |
| 2 | 4811 | Leaburg | 44.10 | 122.68 | 207 | 70 | 50 | 30 | 56 |
| 3 | 4835 | Lemolo Lake | 43.37 | 122.22 | 1244 | 70 | 0 | 0 | 28 |
| 4 | 5020 | Long Creek | 44.72 | 119.10 | 1134 | 20 | 50 | 30 | 36 |
| 2 | 5050 | Lookout Point Dam | 43.92 | 122.77 | 216 | 20 | 40 | 30 | 31 |
| 3 | 5055 | Lost Creek Dam | 42.67 | 122.68 | 482 | 80 | 40 | 30 | 55 |
| 4 | 5139 | Madras | 44.63 | 121.13 | 680 | 60 | 50 | 50 | 54 |
| 4 | 5142 | Madras 2 | 44.67 | 121.15 | 744 | 80 | 50 | 50 | 62 |
| 5 | 5160 | Malheur Ranch Exp. Stn. | 43.98 | 117.02 | 680 | 70 | 30 | 40 | 47 |
| 5 | 5162 | Malheur Refuge Hdq. | 43.28 | 118.83 | 1253 | 80 | 30 | 40 | 51 |
| 5 | 5174 | Malin | 42.00 | 121.32 | 1411 | 50 | 40 | 50 | 45 |
| 4 | 5258 | Mason Dam | 44.67 | 118.00 | 1189 | 90 | 40 | 40 | 60 |
| 5 | 5335 | Mc Dermitt | 42.42 | 117.87 | 1359 | 80 | 90 | 90 | 86 |
| 2 | 5384 | Mc Minnville | 45.23 | 123.18 | 46 | 20 | 30 | 20 | 25 |
| 3 | 5424 | Medford Exp. Stn. | 42.30 | 122.87 | 445 | 20 | 30 | 40 | 27 |
| 3 | 5429 | Medford Airport | 42.37 | 122.87 | 399 | 90 | 40 | 40 | 60 |
| 4 | 5515 | Metolius | 44.58 | 121.18 | 762 | 20 | 70 | 90 | 52 |
| 4 | 5545 | Mikkalo | 45.47 | 120.35 | 472 | 60 | 50 | 30 | 52 |
| 4 | 5593 | Milton Freewater | 45.95 | 118.42 | 296 | 80 | 50 | 40 | 61 |
| 4 | 5610 | Minam | 45.68 | 117.60 | 1100 | 50 | 50 | 40 | 49 |
| 4 | 5641 | Mitchell | 44.58 | 120.18 | 808 | 90 | 80 | 70 | 83 |
| 4 | 5711 | Monument | 44.82 | 119.42 | 610 | 50 | 70 | 70 | 62 |
| 4 | 5734 | Moro | 45.48 | 120.72 | 570 | 80 | 70 | 80 | 75 |
| 1 | 6032 | Newport | 44.58 | 124.05 | 43 | 50 | 10 | 20 | 27 |
| 1 | 6073 | North Bend Airport | 43.42 | 124.25 | 3 | 20 | 20 | 20 | 20 |
| 2 | 6151 | No Willamette Exp. Stn. | 45.28 | 122.75 | 46 | 80 | 40 | 20 | 54 |
| 2 | 6173 | Noti | 44.07 | 123.47 | 137 | 20 | 30 | 10 | 24 |
| 5 | 6179 | Nyssa | 43.87 | 117.00 | 664 | 20 | 60 | 70 | 45 |
| 5 | 6243 | Ochoco Ranger Stn. | 44.40 | 120.43 | 1213 | 20 | 40 | 50 | 33 |
| 5 | 6252 | Odell Lake East | 43.55 | 121.97 | 1463 | 20 | 30 | 50 | 28 |
| 5 | 6294 | Ontario KSRV | 44.05 | 116.97 | 655 | 80 | 50 | 40 | 61 |
| 5 | 6302 | OO Ranch | 43.28 | 119.32 | 1262 | 60 | 50 | 70 | 56 |
| 2 | 6334 | Oregon City | 45.35 | 122.60 | 52 | 50 | 20 | 20 | 32 |
| 1 | 6366 | Otis | 45.03 | 123.93 | 46 | 20 | 30 | 20 | 25 |
| 5 | 6405 | Owyhee Dam | 43.65 | 117.25 | 732 | 60 | 30 | 70 | 46 |
| 5 | 6426 | Paisley | 42.70 | 120.53 | 1329 | 20 | 60 | 70 | 45 |
| 4 | 6466 | Parkdale | 45.53 | 121.57 | 463 | 20 | 30 | 30 | 26 |
| 5 | 6500 | Paulina | 44.13 | 119.97 | 1122 | 60 | 50 | 60 | 55 |
| 4 | 6532 | Pelton Dam | 44.73 | 121.23 | 430 | 80 | 30 | 40 | 51 |
| 4 | 6540 | Pendleton Exp. Stn. | 45.72 | 118.63 | 454 | 60 | 80 | 70 | 71 |
| 4 | 6541 | Pendleton Roundup Park | 45.67 | 118.80 | 322 | 20 | 80 | 70 | 55 |
| 4 | 6546 | Pendleton Airport | 45.68 | 118.85 | 454 | 20 | 80 | 70 | 55 |
| 4 | 6634 | Pilot Rock | 45.48 | 118.82 | 524 | 60 | 80 | 70 | 71 |

| R | STN | Station name | Lat (deg) | Long (deg) | Elev (m) | Aridity (%) S | A | R | C |
|---|---|---|---|---|---|---|---|---|---|
| 4 | 6655 | Pine Grove | 45.12 | 121.37 | 677 | 60 | 70 | 60 | 65 |
| 2 | 6749 | Portland KGW-TV | 45.52 | 122.68 | 49 | 70 | 60 | 30 | 61 |
| 2 | 6751 | Portland Airport | 45.60 | 122.60 | 6 | 80 | 60 | 30 | 65 |
| 1 | 6784 | Port Orford | 42.75 | 124.50 | 15 | 20 | 20 | 10 | 19 |
| 1 | 6820 | Powers | 42.88 | 124.07 | 70 | 20 | 40 | 30 | 31 |
| 5 | 6853 | P Ranch Refuge | 42.82 | 118.88 | 1280 | 20 | 80 | 70 | 55 |
| 5 | 6883 | Prineville | 44.35 | 120.90 | 866 | 60 | 50 | 50 | 54 |
| 3 | 6907 | Prospect | 42.73 | 122.52 | 756 | 90 | 40 | 60 | 62 |
| 5 | 7056 | Redmond | 44.27 | 121.17 | 920 | 20 | 60 | 70 | 45 |
| 5 | 7062 | Redmond Airport | 44.27 | 121.15 | 933 | 70 | 60 | 70 | 65 |
| 4 | 7160 | Richland | 44.77 | 117.17 | 677 | 60 | 40 | 30 | 47 |
| 3 | 7169 | Riddle | 42.95 | 123.35 | 207 | 20 | 40 | 30 | 31 |
| 5 | 7208 | Riverside | 43.50 | 118.07 | 914 | 90 | 50 | 90 | 70 |
| 5 | 7277 | Rocksville | 43.37 | 117.12 | 1119 | 20 | 60 | 80 | 46 |
| 5 | 7310 | Rome | 42.87 | 117.65 | 1039 | 80 | 40 | 80 | 60 |
| 3 | 7331 | Roseburg KQEN | 43.20 | 123.35 | 143 | 60 | 60 | 70 | 61 |
| 5 | 7354 | Round Grove | 42.33 | 120.88 | 1490 | 60 | 50 | 60 | 55 |
| 3 | 7391 | Ruch | 42.23 | 123.03 | 472 | 20 | 30 | 40 | 27 |
| 2 | 7466 | St Helens RFD | 45.87 | 122.82 | 30 | 20 | 40 | 20 | 30 |
| 2 | 7500 | Salem | 44.92 | 123.02 | 61 | 20 | 10 | 10 | 14 |
| 2 | 7586 | Scogginns Dam | 45.48 | 123.20 | 110 | 80 | 30 | 20 | 49 |
| 2 | 7631 | Scotts Mills | 44.95 | 122.53 | 707 | 20 | 40 | 30 | 31 |
| 1 | 7641 | Seaside | 45.98 | 123.92 | 3 | 60 | 10 | 10 | 30 |
| 5 | 7675 | Seneca | 44.13 | 118.97 | 1420 | 70 | 50 | 30 | 56 |
| 3 | 7698 | Sexton Summit | 42.62 | 123.37 | 1170 | 20 | 50 | 60 | 39 |
| 5 | 7736 | Sheaville | 43.12 | 117.03 | 1408 | 50 | 70 | 80 | 63 |
| 2 | 7809 | Silver Creek Falls | 44.87 | 122.65 | 411 | 20 | 30 | 20 | 25 |
| 5 | 7817 | Silver Lake | 43.12 | 121.07 | 1335 | 50 | 30 | 60 | 41 |
| 2 | 7823 | Silverton | 45.00 | 122.77 | 125 | 80 | 50 | 40 | 61 |
| 5 | 7857 | Sisters | 44.30 | 121.55 | 969 | 80 | 60 | 60 | 68 |
| 5 | 8007 | Sprague River | 42.45 | 121.50 | 1329 | 80 | 20 | 50 | 47 |
| 5 | 8029 | Squaw Butte Exp. Stn. | 43.48 | 119.72 | 1420 | 80 | 80 | 80 | 80 |
| 2 | 8095 | Stayton | 44.78 | 122.82 | 131 | 20 | 30 | 20 | 25 |
| 5 | 8173 | Summer Lake | 42.95 | 120.78 | 1277 | 60 | 30 | 80 | 47 |
| 5 | 8250 | Suntex | 43.60 | 119.63 | 1314 | 20 | 70 | 80 | 51 |
| 4 | 8407 | The Dalles | 45.60 | 121.20 | 30 | 60 | 50 | 40 | 53 |
| 5 | 8420 | The Poplars | 43.27 | 120.93 | 1317 | 20 | 40 | 60 | 34 |
| 2 | 8466 | Three Lynx | 45.12 | 122.07 | 341 | 60 | 20 | 30 | 37 |
| 1 | 8481 | Tidewater | 44.42 | 123.90 | 15 | 20 | 30 | 20 | 25 |
| 1 | 8494 | Tillamook | 45.45 | 123.87 | 3 | 20 | 40 | 30 | 31 |
| 3 | 8536 | Toketee Falls | 43.28 | 122.45 | 628 | 80 | 30 | 40 | 51 |
| 2 | 8634 | Troutdale | 45.55 | 122.40 | 9 | 80 | 20 | 20 | 44 |
| 4 | 8726 | Ukiah | 45.13 | 118.93 | 1024 | 20 | 40 | 40 | 32 |
| 4 | 8746 | Union Exp. Stn. | 45.22 | 117.88 | 844 | 20 | 20 | 20 | 20 |
| 4 | 8780 | Unity | 44.43 | 118.23 | 1228 | 90 | 40 | 20 | 58 |
| 5 | 8797 | Vale | 43.98 | 117.25 | 683 | 80 | 40 | 50 | 57 |

| R | STN | Station name | Lat (deg) | Long (deg) | Elev (m) | Aridity (%) S | A | R | C |
|---|---|---|---|---|---|---|---|---|---|
| 5 | 8812 | Valley Falls | 42.48 | 120.28 | 1320 | 60 | 80 | 100 | 74 |
| 1 | 8833 | Valsetz | 44.85 | 123.67 | 354 | 60 | 40 | 10 | 45 |
| 2 | 8884 | Vernonia | 45.87 | 123.18 | 192 | 50 | 40 | 20 | 42 |
| 5 | 8948 | Wagontire | 43.25 | 119.88 | 1442 | 60 | 50 | 80 | 57 |
| 4 | 8985 | Walla Walla | 46.00 | 118.05 | 732 | 20 | 40 | 40 | 32 |
| 4 | 8997 | Wallowa | 45.56 | 117.53 | 890 | 50 | 40 | 20 | 42 |
| 5 | 9176 | Westfall | 44.05 | 117.75 | 957 | 60 | 70 | 80 | 67 |
| 5 | 9290 | Whitehorse Ranch | 42.33 | 118.23 | 1280 | 20 | 70 | 80 | 51 |
| 5 | 9316 | Wickiup Dam | 43.68 | 121.68 | 1329 | 80 | 30 | 60 | 53 |
| 3 | 9464 | Winchester | 43.28 | 123.42 | 140 | 50 | 50 | 50 | 50 |

# APPENDIX B: Secondary Weather Data

Sources of minimum air relative humidity (or related variables) at the different SWD stations.

| Station name | ODD DATA BASE<br>Daily values<br>Min. rel. hum., % | DHA DATA BASE<br>Hourly values<br>Avg. rel. hum., % | CHDD DATA BASE<br>Daily values<br>Dewp. temp., °F | PNHH DATA BASE<br>Hourly values<br>Min. rel. hum., % | Recommended source |
|---|---|---|---|---|---|
| Astoria | 16 years<br>1953-1987 | 31 years<br>1953-1983 | | 5 years<br>1953-1957 | ODD |
| Baker | | 17 years<br>1948-1964 | | 10 years<br>1948-1957 | DHA |
| Boardman | | | 2-5 years<br>1984-1988 | | CHDD |
| Boise, ID | | 36 years<br>1948-1983 | | 10 years<br>1949-1958 | DHA |
| Burns | 3-4 years<br>1984-1987 | 33 years<br>1948-1980 | | 11 years<br>1948-1958 | DHA |
| Eugene | 10-12 years<br>1948-1987 | 36 years<br>1948-1983 | | 11 years<br>1948-1958 | ODD |
| Hermiston | | | 1-9 years<br>1980-1988 | | CHDD |
| Klamath Falls | | 23 years<br>1948-1970 | | 10 years<br>1949-1958 | DHA |
| La Grande | | | | 6 years<br>1948-1953 | PNHH |
| Meacham | | | | 10 years<br>1950-1959 | PNHH |
| Medford | 20-21 years<br>1948-1987 | 36 years<br>1948-1983 | | 10 years<br>1949-1958 | ODD |
| North Bend | | 31 years<br>1948-1978 | | 10 years<br>1950-1959 | DHA |
| Ontario | | | | 7 years<br>1948-1954 | PNHH |
| Pendleton | 20-21 years<br>1948-1987 | 46 years<br>1938-1983 | | 10 years<br>1949-1958 | ODD |
| Portland | 20-21 years<br>1948-1987 | 37 years<br>1948-1984 | | 10 years<br>1949-1958 | ODD |
| Redmond | | 36 years<br>1948-1983 | | 10 years<br>1949-1958 | DHA |
| Roseburg | | 17 years<br>1948-1964 | | 5 years<br>1953-1957 | DHA |
| Salem | 20-21 years<br>1948-1987 | 38 years<br>1948-1985 | | 10 years<br>1949-1958 | ODD |
| Sexton Summit | 4-5 years<br>1948-1987 | 31 years<br>1948-1978 | | 10 years<br>1950-1959 | DHA |
| The Dalles | | 17 years<br>1948-1964 | | | DHA |
| Walla Walla | | 18 years<br>1948-1965 | | 10 years<br>1949-1958 | DHA |

1. Digital Daily Data (ODD)
2. Digital Hourly Airport Data (DHA)
3. Hermiston Digital Daily Data (CHDD)
4. Published Hourly Airport Data (PNHH)

Sources of ratio of actual to maximum possible sunshine hours (or related variables) at the different SWD stations.

| Station name | ODD DATA BASE Daily values Daytime cloud cover* | DHA DATA BASE Hourly values Cloud cover | CHDD DATA BASE Daily values Meas. solar rad. cal $cm^{-2}$ $d^{-1}$ | PMA DATA BASE Monthly values Daytime cloud cover* | ASSR DATA BASE Monthly values Meas. solar rad. kW h $m^{-2}$ | PNSR DATA BASE Monthly values Est. solar rad.** cal $cm^{-2}$ $d^{-1}$ | Recommended source |
|---|---|---|---|---|---|---|---|
| Astoria | 23 years 1965-1987 | 31 years 1953-1983 | | 35 years 1953-1987 | | 5-10 years** 1948-1970 | PNSR |
| Baker | | 17 years 1948-1964 | | | | 5-10 years 1948-1970 | DHA |
| Bend | | | | | 7 years 1977-1983 | | ASSR |
| Boardman | | | 5 years 1984-1988 | | | | CHDD |
| Boise, ID | | 36 years 1948-1983 | | | | | DHA |
| Burns | 7-8 years 1980-1987 | 33 years 1948-1980 | | | | | ODD |
| Coos Bay | | | | | 7 years 1977-1983 | | ASSR |
| Corvallis | | | | | | 5-10 years** 1948-1970 | PNSR |
| Eugene | 23 years 1965-1987 | 36 years 1948-1983 | | 38 years 1949-1986 | 9 years 1975-1983 | 5-10 years 1948-1970 | ASSR |
| Hermiston | | | 9 years 1980-1988 | | 5 years 1979-1983 | | CHDD |
| Klamath Falls | | 23 years 1948-1970 | | | | 5-10 years 1948-1970 | DHA |
| La Grande | | | | | 7 years 1977-1983 | 5-10 years 1948-1970 | ASSR |
| Meacham | | | | | | 5-10 years 1948-1970 | PNSR |

| Station name | ODD DATA BASE Daily values Daytime cloud cover* | DHA DATA BASE Hourly values Cloud cover | CHDD DATA BASE Daily values Meas. solar rad. cal $cm^{-2}$ $d^{-1}$ | PMA DATA BASE Monthly values Daytime cloud cover* | ASSR DATA BASE Monthly values Meas. solar rad. kW h $m^{-2}$ | PNSR DATA BASE Monthly values Est. solar rad.** cal $cm^{-2}$ $d^{-1}$ | Recommended source |
|---|---|---|---|---|---|---|---|
| Medford | 23 years 1965-1987 | 36 years 1948-1983 | | | | 5-10 years** 1948-1970 | PNSR |
| Mountain Home, ID | | | | | | 5-10 years 1948-1970 | PNSR |
| Ontario | | | | | | 5-10 years 1948-1970 | PNSR |
| Pendleton | 23 years 1965-1987 | 46 years 1938-1983 | | 35 years 1949-1983 | | 5-10 years 1948-1970 | ODD |
| Portland | 23 years* 1965-1987 | 37 years 1948-1984 | | 38 years* 1949-1986 | 4 years 1980-1983 | 5-10 years 1948-1970 | ODD |
| Redmond | | 36 years 1948-1983 | | | | 5-10 years 1948-1970 | DHA |
| Roseburg | | 17 years 1948-1964 | | | | 5-10 years 1948-1970 | DHA |
| Salem | 23 years 1965-1987 | 38 years 1948-1985 | | | | | ODD |
| Sexton Summit | 22-23 years 1965-1987 | 31 years 1948-1978 | | 31 years 1948-1976; 1982-1984 | | 5-10 years 1948-1970 | ODD |
| The Dalles | | 17 years 1948-1964) | | | | 5-10 years 1948-1970 | DHA |
| Walla Walla | | 18 years 1948-1965 | | | | | DHA |
| Whitehorse Ranch | | | | | 7 years 1977-1983 | | ASSR |

* Ratio of actual to maximum possible sunshine hours were measured.

** Solar radiation was measured.

1. Digital Daily Data (ODD)
2. Digital Hourly Airport Data (DHA)
3. Monthly Average Data (PMA)
4. Published Estimated/Measured Solar Radiation (PNSR)
5. Atmospheric Sciences Solar Radiation Data (ASSR)
6. Hermiston Digital Daily Data (CHDD)

Sources of daytime windspeed (or related variables) at the different SWD stations.

| Station name | ODD DATA BASE Daily values Avg. windspeed mph x 10 | DHA DATA BASE Hourly values Avg. windspeed knots x 10 | CHDD DATA BASE Daily values Total windrun mi | PNHH DATA BASE Hourly values Avg. windspeed mph | PMA DATA BASE Monthly values Avg. windspeed mph | WRPE DATA BASE Monthly values Total windrun mi | Recommended source |
|---|---|---|---|---|---|---|---|
| Astoria | 4 years 1984-1987 | 31 years 1953-1983 | | 5 years 1953-1957 | 34 years 1953-1986 | 5-7 years 1966-1973 | DHA |
| Baker | | 17 years 1948-1964 | | 10 years 1948-1957 | | | DHA |
| Boardman | | | 2-5 years 1984-1988 | | | | CHDD |
| Boise, ID | | 36 years 1948-1983 | | | | | DHA |
| Burns | 3-4 years 1984-1987 | 33 years 1948-1980 | | 11 years 1948-1958 | | | DHA |
| Corvallis | | | | | | 3-21 years 1966-1987 | WRPE |
| Cottage Grove Dam | | | | | | 12-13 years 1966-1978 | WRPE |
| Detroit Dam | | | | | | 3-22 years 1966-1987 | WRPE |
| Eugene | 4 years 1984-1987 | 36 years 1948-1983 | | 11 years 1948-1958 | 36 years 1949-1984 | | DHA |
| Hermiston | | | 8-9 years 1980-1988 | | | 10-19 years 1966-1987 | CHDD |
| Klamath Falls | | 23 years 1948-1970 | | 10 years 1949-1958 | | 5-10 years 1978-1987 | DHA |
| La Grande | | | | 6 years 1948-1953 | | | PNHH |
| Lookout Point Dam | | | | | | 8-22 years 1966-1987 | WRPE |
| Madras | | | | | | 4-14 years 1974-1987 | WRPE |
| Malheur Refuge Hdq | | | | | | 4-17 years 1966-1987 | WRPE |
| Meacham | | | | 10 years 1950-1959 | | | PNHH |
| Medford | 4 years 1984-1987 | 36 years 1948-1983 | | 10 years 1949-1958 | 36 years 1949-1984 | 3-21 years 1966-1987 | DHA |
| Moro | | | | | | 17-22 years 1966-1987 | WRPE |
| No Willamette Exp. Stn. | | | | | | 15-22 years 1966-1987 | WRPE |
| North Bend | | 31 years 1948-1978 | | 10 years 1950-1959 | | | DHA |
| Ontario | | | | 7 years 1948-1954 | | | PNHH |
| Pendleton | 4 years 1984-1987 | 46 years 1938-1983 | | 10 years 1949-1958 | 35 years 1949-1983 | 12-13 years 1975-1987 | DHA |
| Portland | 4 years 1984-1987 | 37 years 1948-1984 | | 10 years 1949-1958 | 38 years 1949-1986 | | DHA |
| Redmond | | 36 years 1948-1983 | | 10 years 1949-1958 | | | DHA |
| Roseburg | | 17 years 1948-1964 | | 5 years 1953-1957 | | | DHA |
| Salem | 4 years 1984-1987 | 38 years 1948-1985 | | 10 years 1949-1958 | 40 years 1949-1988 | | DHA |

| Station name | ODD DATA BASE Daily values Avg. windspeed mph x 10 | DHA DATA BASE Hourly values Avg. windspeed knots x 10 | CHDD DATA BASE Daily values Total windrun mi | PNHH DATA BASE Hourly values Avg. windspeed mph | PMA DATA BASE Monthly values Avg. windspeed mph | WRPE DATA BASE Monthly values Total windrun mi | Recommended source |
|---|---|---|---|---|---|---|---|
| Sexton Summit | 4 years 1984-1987 | 31 years 1948-1978 | | 10 years 1950-1959 | | | DHA |
| Summer Lake | | | | | | 21-22 years 1966-1987 | WRPE |
| The Dalles | | 17 years 1948-1964 | | | | | DHA |
| Walla Walla | | 18 years 1948-1965 | | | | | DHA |
| Warm Springs Reservoir | | | | | | 6-9 years 1966-1974 | WRPE |
| Wickiup Dam | | | | | | 9-22 years 1966-1987 | WRPE |

1. Digital Daily Data (ODD)
2. Digital Hourly Airport Data (DHA)
3. Monthly Average Data (PMA)
4. Windrun (Pan Evaporimeter Height) Data (WRPE)
5. Hermiston Digital Daily Data (CHDD)
6. Published Hourly Airport Data (PNHH)

# APPENDIX C: Cropmir Program Listing

```
'
'
'                    CROPMIR v. 1.0
'
'
'
'      GENERAL PROGRAM TO ESTIMATE MONTHLY CROP WATER USE AND
'                CROP IRRIGATION REQUIREMENTS
'
'      METHODS:  -  Crop water use
'
'                   a)  FAO Blaney-Criddle w/ USDA adjustments
'                   b)  FAO crop coefficients
'
'                -  Effective precipitation:
'
'                   Soil Conservation Service method
'
'      AUTHORS:  Antonio Martinez-Cob
'                Gabriel Katul
'                Jeffery L. Nuss
'
'                Water Resources Team
'                Dept. of Agricultural Engineering
'                Oregon State University
'                Corvallis, Oregon
'

'
'                    MAIN MODULE
'

'     ----   Declare subroutines and libraries

DECLARE SUB BLACRI ()                ' ----   ETo (Blaney-Criddle) by stations
DECLARE SUB REGETO ()                ' ----   ETo (Blaney-Criddle) by regions
DECLARE SUB MONTHIR ()               ' ----   Monthly IR for each year of record (by regions)
DECLARE SUB DISTRIB ()               ' ----   Distribution of monthly ET crop and monthly IR
DECLARE SUB FINISH ()                ' ----   Warning when a subroutine is finished
DECLARE SUB SCRCLEAN ()              ' ----   Clean screen, except borders
REM $INCLUDE: 'c:\qb45\WRET.ICL'     ' ----   Useful function library

'     ----   Main menu

10    CLS
      BOX 5, 79, 2, 23, 2                  ' ----   Borders of the screen
      LOCATE 2, 39: COLOR 0, 7: PRINT " MENU ": COLOR 7, 0
      LOCATE 23, 35: COLOR 0, 7: PRINT " CROPMIR v. 1.0 ": COLOR 7, 0
      LOCATE 6, 10: COLOR 0, 7: PRINT " 1 "; : COLOR 7, 0
      PRINT "  Monthly reference ET by met. stations"
      LOCATE 8, 10: COLOR 0, 7: PRINT " 2 "; : COLOR 7, 0
      PRINT "  Monthly ref. ET & secondary weather data by climatic regions"
      LOCATE 10, 10: COLOR 0, 7: PRINT " 3 "; : COLOR 7, 0
      PRINT "  Monthly crop ET & net IR by climatic regions"
      LOCATE 12, 10: COLOR 0, 7: PRINT " 4 "; : COLOR 7, 0
      PRINT "  Distribution of monthly crop ET & net IR by climatic regions"
      LOCATE 14, 10: COLOR 0, 7: PRINT " 5 "; : COLOR 7, 0
      PRINT "  Quit the program"
      LOCATE 17, 10: PRINT "Enter your selection  < 1, 2, 3, 4, or 5 >"
      LOCATE 19, 15: INPUT " ", MENU
      SELECT CASE MENU
         CASE 1: CALL BLACRI
         CASE 2: CALL REGETO
         CASE 3: CALL MONTHIR
         CASE 4: CALL DISTRIB
         CASE 5: GOTO 20
         CASE ELSE: BEEP
      END SELECT: GOTO 10

'     ----   Quit the program

20    CALL SCRCLEAN                        ' ----   Clean screen, except borders
      LOCATE 10, 25: INPUT "Are you sure (y/n)  ", QUIT$
      IF UCASE$(QUIT$) = "Y" THEN 30
      GOTO 10
30    CLS
      BOX 20, 50, 8, 16, 1
      LOCATE 11, 25: COLOR 31
      PRINT "Hope to see you again"
      LOCATE 14, 25: PRINT "Bye, friend!"
```

```
COLOR 7
LOCATE 23
END

'
'                              BLACRI
'
'
'
'    ----    Subroutine to compute monthly ref. ET by stations.
'            FAO Blaney-Criddle method with USDA adjustments
'
'
SUB BLACRI STATIC

   '    ----    Dimension variables

   DIM RHMIN(1 TO 12), UDAY(1 TO 12), SUNSH(1 TO 12), RSOL(1 TO 12)
   DIM U24(1 TO 12), U2(1 TO 6), RH(1 TO 6), RAT(1 TO 2, 1 TO 12)
   DIM P(1 TO 2, 1 TO 12), LAT(1 TO 2), NR(1 TO 36, 1 TO 6)
   DIM BB(1 TO 36, 1 TO 6, 1 TO 6)

   '    ----    Borders of the screen

1  CLS
   BOX 5, 79, 2, 23, 1
   LOCATE 2, 30: COLOR 0, 7: PRINT " MONTHLY REF. ET (STATIONS) ": COLOR 7, 0
   LOCATE 23, 35: COLOR 0, 7: PRINT " CROPMIR v. 1.0 ": COLOR 7, 0

   '    ----    Drive/directory for input and output data files

   LOCATE 5, 10: PRINT "Enter drive containing input data files"
   LOCATE 7, 10: INPUT "< x:\path\ >   ", BCINPD$
   LOCATE 10, 10: PRINT "Enter drive to store output data files"
   LOCATE 12, 10: INPUT "< x:\path\ >   ", BCOUTD$
   LOCATE 15, 10: PRINT "Do you wish to correct ETo by elevation"
   LOCATE 17, 10: INPUT "< Y / N >   ", CORREL$
   IF UCASE$(CORREL$) <> "Y" AND UCASE$(CORREL$) <> "N" THEN BEEP: GOTO 1

   CALL SCRCLEAN                     ' ----    Clean screen, except borders
   LOCATE 8, 25: PRINT "Please, wait! ..."
   LOCATE 10, 15: PRINT "Computing reference ET by met. stations"
   BOX 14, 36, 13, 17, 1
   LOCATE 15, 19: PRINT "Station  "
   BOX 42, 70, 13, 17, 1
   LOCATE 15, 47: PRINT "Stations done  "

   '    ----    Open file containing station identification numbers

   INFO$ = BCINPD$ + "STNINFTH.DAT"
   OPEN "I", #1, INFO$
   FOR A = 1 TO 4
      INPUT #1, LL1$
   NEXT A
   BFLAG = 0: DONESTN = 0
   WHILE NOT EOF(1)
      LINE INPUT #1, CODE$
      CODE$ = MID$(CODE$, 3, 4)
      IF CODE$ = "0652" OR CODE$ = "5221" OR CODE$ = "5362" THEN 55
      IF CODE$ = "6213" OR CODE$ = "7554" OR CODE$ = "7559" THEN 55

      LOCATE 15, 28: COLOR 31: PRINT CODE$: COLOR 7
      LOCATE 15, 62: COLOR 31: PRINT DONESTN: COLOR 7

      '    ----    Determine names of input data files

      FILEIN1$ = BCINPD$ + "STN#" + CODE$ + ".PDT"    ' ----    Primary weather
      FILEIN2$ = BCINPD$ + "STN#" + CODE$ + ".SDT"    ' ----    Secondary weather

      '    ----    Determine output file names

      FILEOUT$ = BCOUTD$ + "STN#" + CODE$ + ".ETR"
      PFLAG = 0: RATFLAG = 0

      '    ----    Open primary weather data file

      OPEN "I", #2, FILEIN1$
      INPUT #2, STATCODE, ELEV, LATITUDE$, ARIDRAT
      HEMIS$ = RIGHT$(LATITUDE$, 1)
      LATITUD = VAL(LATITUDE$)
      RANF$ = "RAN": PF$ = "PN"
      IF UCASE$(HEMIS$) = "S" THEN RANF$ = "RAS": PF$ = "PS"
```

```
        '    ----   Open output files and store heading parameters

        OPEN "O", #3, FILEOUT$
        PRINT #3, STATCODE
        ARIDRAT = ARIDRAT / 100

        '   ----   Read secondary weather data

        OPEN "I", #7, FILEIN2$
        INPUT #7, STATCODE
        WHILE NOT EOF(7)
           INPUT #7, MON, RHMIN(MON), RSOL(MON), SUNSH(MON), U24(MON), UDAY(MON)
        WEND
        CLOSE #7

        '    ----   Read primary weather data and estimate ref. ET

        WHILE NOT EOF(2)
           INPUT #2, ANNEE, MONTH, TMAX, TMIN
           GOSUB 60                    ' ----   Mean daily percentage of annual daytime hours
           GOSUB 100                   ' ----   Aridity effects and reference ratios
           ARIDADJ = ARIDRAT * ARID
           TMED = (TMAX + TMIN) / 2 - ARIDADJ
           IF SUNSH(MONTH) > 0 THEN 40
           GOSUB 160                   ' ----   Atmospheric solar radiation (mm/d)
           SUNSH(MONTH) = (RSOL(MONTH) / 59) / (.5 * RAAT) - .5
40         IF UDAY(MONTH) > 0 THEN 50
           UDAY(MONTH) = U24(MONTH) * (2 / 3) * (1000 / 43200)
50         F = P * (.46 * TMED + 8.13)
           A = .0043 * RHMIN(MONTH) - SUNSH(MONTH) - 1.41
           GOSUB 110                   ' ----   b coefficient
           IF UCASE$(CORREL$) = "N" THEN ETO = A + B * F: GOTO 52
           ETO = (A + B * F) * (1 + ELEV / 10000)
52         ETO = ETO * REFRAT          ' ----   Monthly ref. ET, mm/d
           IF ETO < 0 THEN ETO = 0
           IF UCASE$(CORREL$) = "N" THEN 53
           PRINT #3, USING "#### ## ##.#"; ANNEE; MONTH; ETO
           GOTO 54
53         PRINT #3, USING "#### ## ##.##"; ANNEE; MONTH; ETO
54      WEND
        CLOSE #2: CLOSE #3
        DONESTN = DONESTN + 1
55   WEND
     CLOSE #1

     CALL SCRCLEAN                     ' ----   Clean screen, except borders

     LOCATE 7, 15: PRINT "Reference ET computed for all met. stations"
     CALL FINISH
     GOTO 200

     '    ----   Mean daily percentage of annual daytime hours

60   IF PFLAG = 1 THEN 90
     FCONT = 1
     OPEN "I", #4, PF$
     FOR LIN = 1 TO 4
        INPUT #4, LIN$                 ' ----   Read table headings
     NEXT LIN
70   INPUT #4, LAT(FCONT)
     FOR MON = 1 TO 12
        INPUT #4, P(FCONT, MON)
     NEXT MON
     IF LATITUD >= LAT(FCONT) THEN 80
     IF (LAT(FCONT) > 40 AND (LATITUD - LAT(FCONT)) >= -2) THEN FCONT = 2
     IF (LAT(FCONT) <= 40 AND (LATITUD - LAT(FCONT)) >= -5) THEN FCONT = 2
     GOTO 70
80   CLOSE #4
90   P = P(2, MONTH) - (P(2, MONTH) - P(1, MONTH)) * (LATITUD - LAT(2)) / (LAT(1) - LAT(2))
     PFLAG = 1
     RETURN

     '    ----   Aridity effects and reference ratios

100  SELECT CASE MONTH
        CASE 1: ARID = 0: REFRAT = 1
        CASE 2: ARID = 0: REFRAT = 1
        CASE 3: ARID = 0: REFRAT = 1
        CASE 4: ARID = 1: REFRAT = 1.21 / 1.15
        CASE 5: ARID = 1.5: REFRAT = 1.14 / 1.15
        CASE 6: ARID = 2: REFRAT = 1.07 / 1.15
        CASE 7: ARID = 3.5: REFRAT = 1.01 / 1.15
        CASE 8: ARID = 4.5: REFRAT = 1 / 1.15
        CASE 9: ARID = 3: REFRAT = 1.08 / 1.15
        CASE 10: ARID = 0: REFRAT = 1.22 / 1.15
```

```
      CASE 11: ARID = 0: REFRAT = 1
      CASE 12: ARID = 0: REFRAT = 1
   END SELECT: RETURN

   '    ----    Interpolate b coefficient

110   IF BFLAG = 1 THEN 120
      OPEN "I", #5, "BTABLE"
      FOR LIN = 1 TO 3
         INPUT #5, LIN$                   ' ----   Read table headings
      NEXT LIN
      INPUT #5, LIN$
      FOR Y = 1 TO 6
         INPUT #5, RH(Y)                  ' ----   Six values of relative humidity
      NEXT Y
      ZZ = 0                              ' ----   Set counter to zero
      K = 1                               ' ----   K = 1 corresponds to U2(1) = 0, and K = 6 to
U2(6) = 10 m/s
      FOR Z = 1 TO 36                     ' ----   Read 36 lines from the table
         ZZ = ZZ + 1
         IF ZZ = 7 THEN K = K + 1: ZZ = 1
         INPUT #5, U2(K)                  ' ----   First value of each line is Uday
         INPUT #5, NR(ZZ, K)              ' ----   Second value of each line is n/N
         FOR Y = 1 TO 6
            INPUT #5, BB(ZZ, Y, K)        ' ----   Next 6 values of each line are b coefficients
         NEXT Y
      NEXT Z
      CLOSE #5
120   BFLAG = 1
      IF UDAY(MONTH) < 2 THEN K1 = 1: GOTO 130
      IF UDAY(MONTH) < 4 THEN K1 = 2: GOTO 130
      IF UDAY(MONTH) < 6 THEN K1 = 3: GOTO 130
      IF UDAY(MONTH) < 8 THEN K1 = 4: GOTO 130
      K1 = 5
130   K2 = K1 + 1
      IF RHMIN(MONTH) <= 20 THEN Y1 = 1: GOTO 140
      IF RHMIN(MONTH) <= 40 THEN Y1 = 2: GOTO 140
      IF RHMIN(MONTH) <= 60 THEN Y1 = 3: GOTO 140
      IF RHMIN(MONTH) <= 80 THEN Y1 = 4: GOTO 140
      Y1 = 5
140   Y2 = Y1 + 1
      IF SUNSH(MONTH) <= .2 THEN Z1 = 1: GOTO 150
      IF SUNSH(MONTH) <= .4 THEN Z1 = 2: GOTO 150
      IF SUNSH(MONTH) <= .6 THEN Z1 = 3: GOTO 150
      IF SUNSH(MONTH) <= .8 THEN Z1 = 4: GOTO 150
      Z1 = 5
150   Z2 = Z1 + 1
      B11 = BB(Z1, Y1, K1) + ((SUNSH(MONTH) - NR(Z1, K1)) / .2) * (BB(Z2, Y1, K1) - BB(Z1, Y1,
K1))
      B12 = BB(Z1, Y2, K1) + ((SUNSH(MONTH) - NR(Z1, K1)) / .2) * (BB(Z2, Y2, K1) - BB(Z1, Y2,
K1))
      B1 = B11 - ((RHMIN(MONTH) - RH(Y1)) / 20) * (B11 - B12)
      B21 = BB(Z1, Y1, K2) + ((SUNSH(MONTH) - NR(Z1, K1)) / .2) * (BB(Z2, Y1, K2) - BB(Z1, Y1,
K2))
      B22 = BB(Z1, Y2, K2) + ((SUNSH(MONTH) - NR(Z1, K1)) / .2) * (BB(Z2, Y2, K2) - BB(Z1, Y2,
K2))
      B2 = B21 - ((RHMIN(MONTH) - RH(Y1)) / 20) * (B21 - B22)
      B = B1 + ((UDAY(MONTH) - U2(K1)) / 2) * (B2 - B1)
      RETURN

   '    ----    Interpolate atmospheric radiation

160   IF RATFLAG = 1 THEN 190
      FCONT = 1
      OPEN "I", #6, RANF$
      FOR LIN = 1 TO 3
         INPUT #6, LIN$                   ' ----   Read table headings
      NEXT LIN
170   INPUT #6, LAT
      FOR MON = 1 TO 12
         INPUT #6, RAT(FCONT, MON)
      NEXT MON
      IF (LATITUD - LAT) >= -2 THEN FCONT = 2
      IF (LATITUD >= LAT) THEN 180
      GOTO 170
180   CLOSE #6
190   RAAT = RAT(2, MONTH) - (LATITUD - LAT) / 2 * (RAT(2, MONTH) - RAT(1, MONTH))
      RATFLAG = 1
      RETURN

200 END SUB
```

```
'
'                              FINISH
'
'
'   ----   Warning when ending a specific procedure
'
'
'
SUB FINISH STATIC

   LOCATE 9, 15: PRINT "Press any key to go to the main menu"
   FOR BPX = 1 TO 3
      BEEP
   NEXT BPX
   LOCATE , , 0: WHILE INKEY$ = "": WEND

END SUB

'
'                             SCRCLEAN
'
'
'   ----   Clean screen, except borders
'
'
SUB SCRCLEAN STATIC

   FOR I = 3 TO 22
      LOCATE I, 6: PRINT STRING$(72, " ")
   NEXT I

END SUB
```