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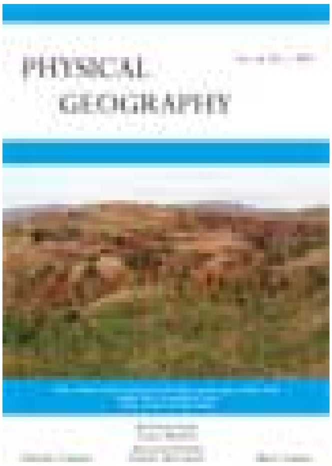

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MODIFIED DE MARTONNE ARIDITY INDEX: APPLICATION TO THE NAPA BASIN, CALIFORNIA

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MODIFIED DE MARTONNE ARIDITY INDEX: APPLICATION TO THE NAPA BASIN, CALIFORNIA

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Abstract: Because of its ease of calculation, the de Martonne aridity index (I_{dM}) is used frequently by investigators for identifying susceptibility to drought conditions. However, application of the classical I_{dM} formula in some geographical areas does not lead to a correct or complete configuration of drought occurrence. This paper proposes a modified index (I_{Mod}) with consideration of a general water-budget equation, instead of precipitation alone as in the I_{dM}. This equation may contain different components in accordance with the season to which it refers; a pattern of three seasons is considered for the Napa Basin area. Equation inputs are averaged monthly values. Assessment is affected by a long series of factors, such as meteorological conditions, evapotranspiration, land morphology and runoff, subsurface influx and drainage capacity, soil cover/use, and irrigation. Since geographical conditions dramatically change with the seasons, the I_{Mod} variation is large. In comparison with the Palmer drought severity index, the main advantage of the newly derived formula is its ease of use under such seasonally changing conditions. It is concluded that use of the I_{Mod} allows a more detailed description of drought character, enlarging the range considered for the classical I_{dM} categories. The main objective of this approach is to provide a basis for a more comprehensive consideration of diversification in water- and land-resource planning. Although applied to the Napa Basin, California, the general water-budget equation included in the I_{Mod} could be adapted successfully to different landscapes. [Key words: de Martonne aridity index, Palmer drought severity index, drought, Napa Basin, California.]

INTRODUCTION

The impacts of the most recent severely dry years throughout the United States (1976–1977 and 1987–1992) have demonstrated that potential vulnerability to drought has been largely underestimated (Wilhite and Rhodes, 1994). For conditions in the United States, the classification of droughts commonly is based on the Palmer drought severity index, or PDSI (Palmer, 1965; California Department of Water Resources, 1978; Williams and Balling, 1996). In this index, negative values refer to dry conditions, whereas positive ones denote wetness. The range of values from –1 to –2 indicates relatively low to moderate dry situations, the range from –2 to –4 shows moderate to high droughts, and the interval –4 to –6 refers to drought occurrences ranging from severe to extreme. For a more effective application of the PDSI, each state within the United States has been assigned a frequency associated with a certain sequence of years, roughly indicating the probability that a severe to extreme drought may occur during a given time interval. Currently, PDSI thresholds

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are used to trigger specific state-level responses, including requests for federal assistance, as the principal criterion for drought-related disaster designation (Wilhite and Rhodes, 1994). Disadvantages of the use of the PDSI include: (1) the huge number of terms defined by Palmer (1965) and their too complex use; (2) the poor reliability of values calculated for mountainous areas because of the dependence on soil-moisture data, and limited use of the latter as a measure of hydrologic drought for water-management purposes (Alley, 1984); and (3) the slow response in characterization of agricultural drought, and the delay in characterization of stream-flow and groundwater variation (Soulé, 1992). In addition, one PDSI value usually is associated with an area as large as an entire state or group of states or is used by some agencies as a constant over several years (California Department of Water Resources, 1978; Wilhite and Rhodes, 1994), being too little associated with the seasonal change in meteorological conditions.

In a comparative study of different climatic indices, for Romanian conditions, Cernescu (1934) highlighted the usability of the de Martonne (1920) aridity index in an evident correlation with zonal types of soil-vegetation patterns (Table 1). The de Martonne expression I_{dM} is a ratio that can be used for either annual or monthly characterizations, with the difference that in the latter case the numerator contains the multiplier 12. In Equation 1, P_m (mm) represents the monthly average precipitation amount and T_m (°C) designates the monthly average temperature value:

$$I_{dM} = \frac{12\, P_m}{T_m + 10}. \tag{1}$$

Values smaller than 10 generally indicate conditions of severe drought, with complete absence of water in river courses and compulsory irrigation of agricultural land. For index values between 10 and 30, river flow is temporary and discharge values may be modest to medium; the vegetation type corresponds to medium steppe. For values greater than 30, river flow becomes permanent and abundant, and conditions for forest vegetation may be present. By definition, I_{dM} is always positive.

The I_{dM} is still being used for its ease in characterizing a climatic zone. Weck (1970) based his climatic model for Germany on the classical I_{dM} and extended it later to the tropics to define the growing season of forest plots (Iverson et al., 1994). In his study of opportunities for irrigation development, Botzan (1974) referred to the classification of hydroclimatic character defined by the de Martonne index and developed new concepts in agricultural drought. Roberts (1993) assessed the annual I_{dM} to compare the climate of two desert zones—Phoenix, Arizona, and Ürümqi, in northwestern China.

Application of the classical I_{dM} formula, however, may not lead to a correct or complete configuration of climatic character. The modified form of the aridity index (I_{Mod}) proposed in this paper is based on a water-budget equation that considers both natural conditions and land-use aspects. Two categories of monthly hydrologic-balance factors are discussed in the paper—inflows (precipitation, irrigation, and subsurface influx) and outflows (evapotranspiration, subsurface and deep

Table 1. Main Classes of I_{dM} Values

I_{dM} value	Climatic character	Character of river course	Phyto-pedologic character
< 10	Severe drought	Absent	Aridity vegetation
10 to 30	Intermediate	Temporary	Medium steppe
> 30	High wetness	Abundant	Conditions for forest

drainage, and runoff). All are directly or indirectly influenced by meteorological conditions and recurrence, land morphology, geological patterns and drainage capacity, soil cover and land use, and irrigation management. For simplification of the water-budget model presented in this paper, it is assumed that the 12 months of an average year can be grouped, for Napa Basin conditions, into three seasons—(1) dry season (May–September), (2) intermediate season (includes March and April as well as October and November), and (3) wet season (December–February). In each of these seasons, the general water-budget equation would have a specific form. In order to determine the hydrometeorological conditions on an average monthly basis and differentiated into the three seasons, the multiannual (1958–1970) database included in the Soil Conservation Service survey of Napa County soils (1978) has been used. However, some minor corrections on those averaged values have been applied by considering the 1971–1995 meteorological records of the National Climatic Data Center (1971–1995).

This paper illustrates the applicability of the I_{Mod} for the Napa Basin, California. It is concluded that use of the modified index makes possible a more detailed description of drought character, in close relation with the land cover/use situation, thus enlarging the range considered for the classical I_{dM} categories. The final goal of this approach is to facilitate a more comprehensive consideration of diversification in water- and land-resource planning. In addition, the general water-budget equation included in the I_{Mod} could be extended successfully and adapted to different landscapes.

STUDY AREA

The Napa Basin, with an area of about 800 km^2, extends between latitudes 38°00′ N and 38°40′ N and belongs to the San Francisco Bay hydrologic zone (California Department of Water Resources, 1994). Most of the basin is located in Napa County and is one of several valleys between the parallel, northwest-trending ridges of the California Coast Ranges (Fig. 1). The Napa River, with its source north of Calistoga, flows southeastward and empties into San Pablo Bay. As shown in Figure 1, the Napa Basin covers the western half of Napa County between Pope Valley on the east and the Napa–Sonoma county boundary to the west. The Upper Napa Basin, north of Napa City, and the Napa Marsh form the two main parts of the watershed.

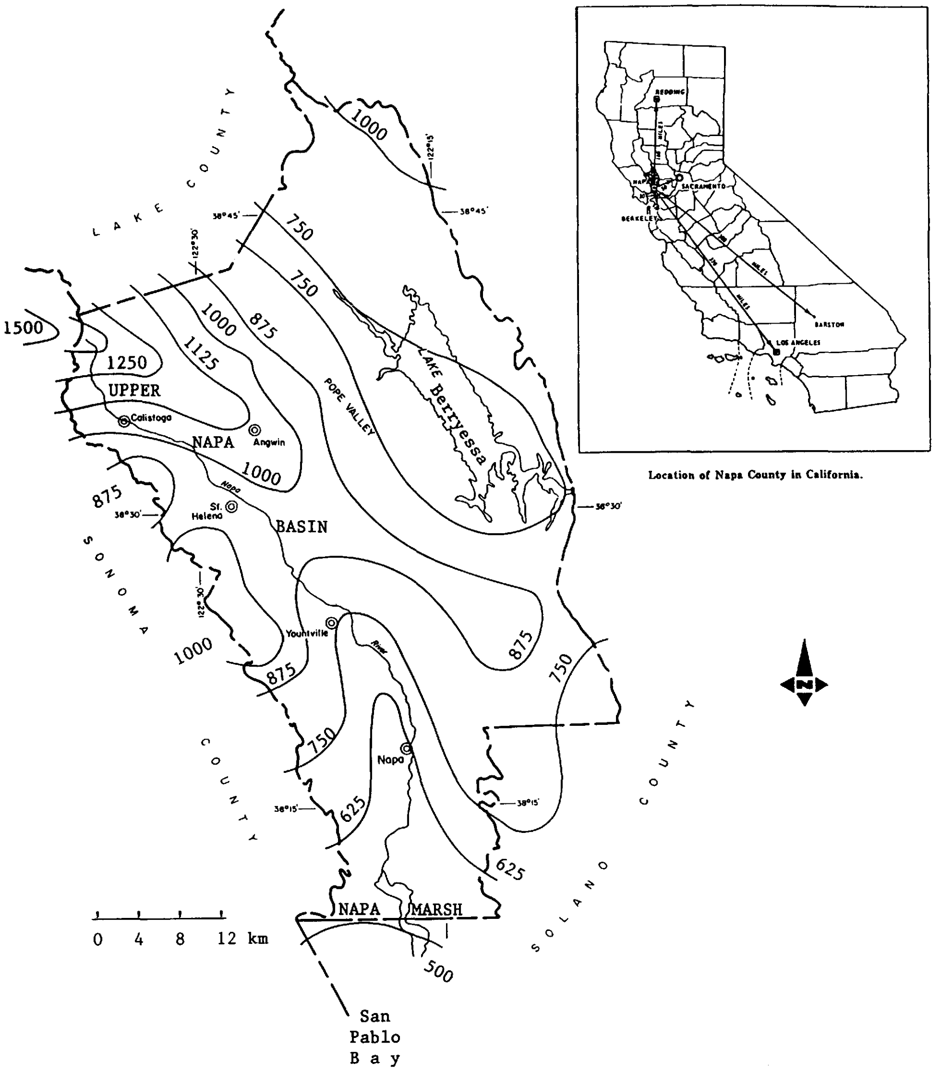

Fig. 1. Napa River Basin, California, and average annual precipitation (1958–1970) over Napa County (isohyets in mm) (Soil Conservation Service, 1978).

The Upper Napa Basin

The Upper Napa Basin is surrounded on its northern two-thirds by mountainous ridges rising as high as 1000 m, but descending southward to 100 m. As a result, during the summer, the basin is protected from the hot conditions of California's Central Valley. The Pacific Ocean provides a source of cool moist air, and the steady flow of marine air from the west and southwest preserves moderate temperature values throughout the year (Soil Conservation Service, 1978). The Napa Basin also has climatic subzones, differentiated in terms of precipitation and evaporation rather than thermal variations. Thus, average annual temperatures at Angwin (elev. 540 m) approximate 13.5 to 14.0°C, whereas at Napa City (elev. 20 m) they range between 14.5 and 15.0°C. At Angwin, however, on a multiannual average basis, precipitation approximates 900 to 1200 mm/yr and evaporation may exceed 1600 mm/yr, whereas at Napa City precipitation ranges from 550 to 650 mm/yr and evaporation equals 2000 mm/yr. In the higher ridges of the basin, above 1000 m, average precipitation is nearly 1500 mm/yr. Farther south in the basin, where annual average temperature may exceed 15.0°C, evaporation rates range from 2000 to 2200 mm/yr (National Climatic Data Center, 1971–1995). Under severe drought conditions, differences between precipitation and evaporation are significant. Thus, in 1976, while precipitation was as low as 260 mm at Napa City and close to 300 mm at Angwin, total potential evaporation exceeded 2200 mm and 1850 mm, respectively. Such low precipitation and high evaporation values associated with altitudes lower than 300 m were encountered over 50 to 60% of the basin (Soil Conservation Service, 1978).

In general, temperatures vary significantly throughout the basin because of differences between mountainous and flat lowland terrain. The greatest variation in temperature occurs in the summer, but winters are generally mild with occasional cold spells. The last freezing temperature in the spring generally occurs in March, the first freeze in the fall in November. The growing season ranges from 215 to 260 days (Soil Conservation Service, 1978).

Soils in the Upper Napa Basin fall into one of two classes—(1) well-drained to poorly drained soils on moderately steep to nearly level lands; and (2) excessively to well-drained soils on gently to very steeply sloping lands. Soils in the former category encompass approximately 35 to 40% of the basin, along the Napa River and its tributaries, on alluvial fans and flood plains where elevation ranges between 15 and 150 m. These soils consist of loamy to clayey alluvium derived ultimately from sedimentary and igneous rocks (Soil Conservation Service, 1978). Although their characteristic plant cover may consist of annual grasses, willows, various berry bushes, and oaks, their uses often include wine grape and fruit production because of their suitability for vineyards and orchards. In other areas protected from flooding, these soils are used for small grain, oat hay, and annual pasture. The second class of soils covers 60 to 65% of the area, embracing gravelly loams to clayey loams at elevations ranging between 70 and 1000 m (Soil Conservation Service, 1978). At higher elevations and on steeper slopes, the land may be used for dryland hay and grain production or may be appropriate for wildlife habitat and range. Limited areas have been covered with vineyards and orchards.

The Napa Marsh

The Napa Marsh, covering the southern 175 km^2 of the basin, is an independent tidal subunit located north of San Pablo Bay. It consists of natural salt marsh (15%), sloughs and streams (10%), salt production ponds (20%), and parts of reclaimed marsh used as agricultural lands (more than 50%) (California Department of Fish and Game, 1977). A variety of municipal facilities, including waste disposal, operate near or in the marsh.

The general climatic pattern of the Napa Marsh is determined by its proximity to the Pacific Ocean through the San Francisco Bay and San Pablo Bay and is characterized by mean annual temperatures lower than those at Napa City by about 1.0 to 1.5°C. Coastal fog may cover the marsh at any season. Annual average precipitation totals about 510 mm but can be reduced by 40 to 60% in a very dry year. Evaporation rates range from 1200 mm to about 1800 mm.

METHODS

Modified de Martonne Aridity Index

The modified version of the de Martonne index (I_{Mod}), proposed here, on a monthly basis may be defined by the general equation

$$I_{Mod} = F_T \cdot F_B, \tag{2}$$

in which F_T $(°C)^{-1}$ and F_B (mm) are, respectively, the temperature and water-budget factors:

$$F_T = \frac{12}{T_m + 10} \tag{3}$$

and

$$F_B = a \cdot P_m + b \cdot IR_m + c \cdot INF_m - d \cdot ET_m - e \cdot D_m - f \cdot RO_m, \tag{4}$$

where the m subscript denotes the monthly basis of the calculation; P_m is the precipitation rate (mm); IR_m is the agricultural irrigation rate (mm); INF_m is the subsurface inflow rate (mm); ET_m is the evapotranspiration rate (mm); D_m is the subsurface drainage, including vertical seepage (mm); RO_m is the runoff rate (mm); and *a*, *b*, *c*, *d*, e, and *f* are dimensionless geographical condition coefficients. The meaning of T_m is the same as in Equation 1.

Each of the conjectural coefficients *a* through *f* in Equation 4, which correspondingly affect each water-budget component, may have an independent determination. However, since not all of the water-budget components occur independently of one another, it is more practical to use certain relationships between precipitation and the other hydrologic factors, rather than typical *a* to *f* coefficient estimates. In such cases, all coefficient values may be set equal to 1, and from Equation 4 only the most significant contributing factors would be taken into consideration, being calculated through one of the various procedures available for United States conditions (Austin, 1965; U.S. Department of Agriculture, 1975; Wischmeier and Smith, 1978; Patry and Mariño, 1984; Young et al., 1989) or for other geographic regions (Botzan, 1972; Bendoricchio and Di Luzio, 1993; Botzan and Necula, 1995; Necula, 1995; Lenzi and Di Luzio, 1997).

The influence of time on the quantified value of the modified index ($I_{Mod,quant,t}$) has been tested in two ways—the effect of previous month (m – 1) on the current month (m), for the same year j; and the effect of the previous year (j – 1) on the current year (j), for the same month m. In both cases, the same type of time-dependence formulation has been considered. Basically, the interrelation between two consecutive values of the modified index, $I_{Mod,t-1}$ and $I_{Mod,t}$ (no matter if t indicates the rank in a monthly or a yearly series)

$$I_{Mod,quant,t} = \alpha\, I_{Mod,t} + (1-\alpha)\, I_{Mod,t-1} \tag{5}$$

has been considered in the following way:

$$\text{If } r \begin{array}{ll} > 0.5 & \text{then } \alpha = .75 \\ = 0.2 \text{ to } 0.5 & \text{then } \alpha = .90 \\ < 0.2 & \text{then } \alpha = 1.00. \end{array} \tag{6}$$

In Equation 6, the ratio r practically compares the two consecutive values, in the following manner:

$$r = (I_{Mod,t} - I_{Mod,t-1}) / I_{Mod,t}. \tag{7}$$

For the 1958–1995 climatic records for the Napa Basin, situations in which $r > 0.5$ were extremely rare, the ones when $r = 0.2$ to 0.5 had a frequency of about 10%, and those in which $r < 0.2$ occurred in almost 90% of the cases; thus the impact of Equation 5 on the values illustrated in Figures 3 to 5 was considered negligible. This consideration is strengthened because values in Figures 3 to 5 are not calculated on a monthly basis but are averaged on a seasonal one (ID = 1, 2, 3).

By comparing the classical form in Equation 1 to the modified one in Equation 2, it can be inferred that the P_m factor has been replaced with the more complex expression in Equation 4. Not all of the terms in Equation 4 are necessarily significant for every subzone of the Napa Basin and every season of the year. Table 4 is created by applying a "most significant contributing factors" assumption to water-budget calculations.

Soil Zoning Model

A 50-cell schematization, with an elemental area of 16 km^2 for each square cell, was selected to depict the differentiated geographical conditions for the Napa Basin (Fig. 2). The upper 39 cells include the Upper Napa Basin, whereas the 11 remaining cover the Napa Marsh. Numbers assigned, based on the NW→SE rule of numbering, designate the cells with the most important urban localities. The land/vegetation resource, impacted by drought occurrence, has been considered to fall within one of the following four categories—agricultural, rural, urban, and wild (Fig. 2). Use of GIS, with more detailed land-coverage information, would provide a tool affording superior variability and differentiation in detecting the environ-

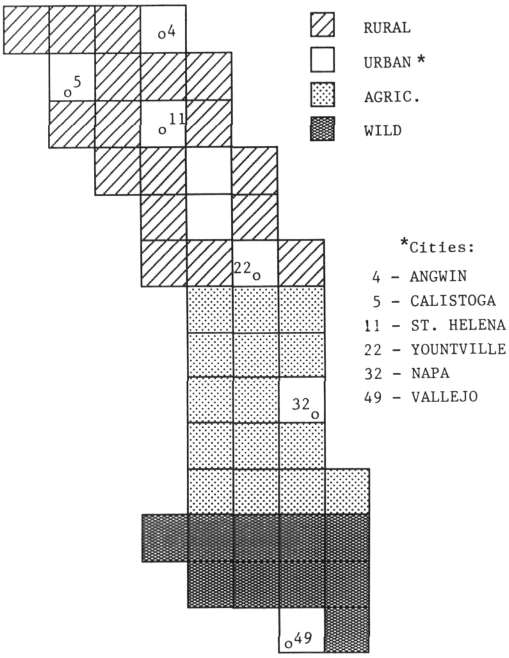

Fig. 2. Land-use/cover resource schematization for the Napa Basin.

mental impacts of a drought event. However, for the purpose of testing the new aridity index, the more expeditious way of using averaged conditions in each cell was preferred.

In order to schematize the monthly water-budget factor (F_B) in Equation 4, it is convenient to start from a two-class drainage capability criterion (Soil Conservation Service, 1978), as shown in Table 2. This table substantiates the drainage (D) and runoff (RO) percentages—from precipitation (P) rates—for different land-slope (S) and vegetation-cover (f) situations. The drainage and runoff percentages have been estimated by superposing soil drainage and slope conditions (Soil Conservation Service, 1978) over land-use and land-cover conditions (California Department of Water Resources, 1969–1994). On the basis of the fact that drainage and runoff are functions not only of geomorphology but also of rainfall regime, averaged meteorological data of the historical period 1958–1970 were considered in the calculation (Soil Conservation Service, 1978) to obtain a more accurate characterization of precipitation components. Consideration of a rainfall-intensity pattern with high- and low-value occurrences also may have contributed to broadening the illustrative power of the example. More explicitly, to determine the relative ratios between certain budget factors, a series of other criteria have been considered, including soil texture, soil drainage capacity, average land slope, average density of vegetation, monthly range of air temperature, and average diurnal rainfall intensity. To some extent, the process of differentiation into specific ranges of values for the ratios listed above must be considered a subjective process. In the absence of a tabular, form-based procedure standardizing all types of geographical conditions, quantifi-

Table 2. Drainage (D) and Runoff (RO) Properties in the Napa Basin

Soil type	Land slope	Vegetation cover	Rainfall	
			High intensity[a]	Low intensity[b]
Poor to good drainage	Flat ($S < 3\%$)	Sparse ($f > 0.5$)	$D = 0.2\,P$, $RO = 0.3\,P$	$D = 0.2\,P$, $RO = 0.2\,P$
		Dense ($f < 0.5$)	$D = 0.3\,P$, $RO = 0.2\,P$	$D = 0.2\,P$, $RO = 0.1\,P$
	Sloping ($S > 3\%$)	Sparse ($f > 0.5$)	$D = 0.1\,P$, $RO = 0.3\,P$	$D = 0.1\,P$, $RO = 0.2\,P$
		Dense ($f < 0.5$)	$D = 0.2\,P$, $RO = 0.2\,P$	$D = 0.1\,P$, $RO = 0.1\,P$
Good to excessive drainage	Gentle ($S < 5\%$)	Sparse ($f > 0.5$)	$D = 0.3\,P$, $RO = 0.4\,P$	$D = 0.3\,P$, $RO = 0.3\,P$
		Dense ($f < 0.5$)	$D = 0.4\,P$, $RO = 0.3\,P$	$D = 0.4\,P$, $RO = 0.2\,P$
	Steep ($S > 5\%$)	Sparse ($f > 0.5$)	$D = 0.3\,P$, $RO = 0.6\,P$	$D = 0.3\,P$, $RO = 0.5\,P$
		Dense ($f < 0.5$)	$D = 0.3\,P$, $RO = 0.5\,P$	$D = 0.3\,P$, $RO = 0.4\,P$

[a] $I > 25$ mm/24-hr.
[b] $I < 25$ mm/24-hr.

cation of ratios between major hydrologic components would be based on existing handbooks and past investigation methods (Austin, 1965; Botzan, 1972; U.S. Department of Agriculture, 1975; Wischmeier and Smith, 1978; Bendoricchio and Di Luzio, 1993; Necula, 1995; and others).

Hypothetical coefficients in Table 2 for each land-use or land-cover category within every temperature-precipitation deficit case have been set to illustrate the development of one modified aridity index model, applied to the Napa Basin. Coefficient values are based on the following assumptions:

1. The monthly precipitation rate (P) is considered, in any season, at its full measured value; in Equation 4, $a = 1.0$.

2. Whereas wild vegetation is never irrigated ($IR_w = 0$), irrigation water delivered to vegetation (IR) is differentially distributed on agricultural, rural, and urban land. The agricultural irrigation rate, in cases of a water deficit ($ET - P$) greater than 150 mm, may be 66 to 100% higher than in less-deficient situations ($0 < ET - P < 150$ mm). This rate also is assumed to have a greater value in better-drained areas (66 to 100%). On rural land, irrigation water (IR_r) would be used on average in an amount equivalent to 50% of the total distributed to agriculture (IR_a)—that is, $IR_r = 0.50\ IR_a$. At the same time, the share of irrigated land in rural zones (b_r) taken globally is assumed to represent 40% of the total land in agricultural use (b_a)—i.e., $b_r = 0.40\ b_a$. For urban zones, vegetation areas (where irrigation rate and irrigated percentage are IR_u and b_u, respectively) are considered to be $IR_u = 0.60\ IR_a$ and $b_u = 0.45\ b_a$.

3. Subsurface inflow (INF) may play an important role in situations in which, for example, excess upland rainfall reaches lower zones because of a steep slope in the water table. In general, compared with the other components in Equation 4, subsurface flow may be considered to be negligible.

4. Evapotranspiration (ET), especially within the interval April–October, has a strong influence on water-deficit calculations. However, since the impact on vegetation is not simply a linear function of potential evapotranspiration (ETP) (Persaud, 1977), the approximation used in this model equals ET with different percentages

Table 3. Geographical Criteria and Assumptions for Monthly (m), Average (ave) Water-Budget Assessment

		$T_{m,ave} < 16$ (°C)		$T_{m,ave} > 16$ (°C)	
Soil type	Land use/cover	$ET_m-P_m < 150$ (mm)	$ET_m-P_m > 150$ (mm)	$ET_m-P_m < 150$ (mm)	$ET_m-P_m > 150$ (mm)
Poor to good drainage	Agric.	$IR_a = 0.4$ (ET–P)	$IR_a = 0.8$ (ET–P)	$IR_a = 0.6$ (ET–P)	$IR_a = 1.2$ (ET–P)
	Rural	d·ET = 0.80 E	d·ET = 0.90 E	d·ET = 0.85 E	d·ET = 0.95 E
	Urban	d·ET = 0.50 E	d·ET = 0.60 E	d·ET = 0.55 E	d·ET = 0.65 E
	Wild	d·ET = 0.85 E	d·ET = 0.95 E	d·ET = 0.90 E	d·ET = 1.00 E
Good to excessive drainage	Agric.	$IR_a = 0.8$ (ET–P)	$IR_a = 1.5$ (ET–P)	$IR_a = 1.2$ (ET–P)	$IR_a = 2.0$ (ET–P)
	Rural	d·ET = 0.65 E	d·ET = 0.75 E	d·ET = 0.60 E	d·ET = 0.70 E
	Urban	d·ET = 0.45 E	d·ET = 0.55 E	d·ET = 0.40 E	d·ET = 0.50 E
	Wild	d·ET = 0.75 E	d·ET = 0.85 E	d·ET = 0.80 E	d·ET = 0.90 E

(d) of the full measured rate of evaporation (E). Thus, on agricultural lands ET is considered to be equal to the E rates (d = 1.00) provided by specialized meteorological stations (National Climatic Data Center, 1971–1995); on the other land-use/cover categories the d percentages are variably differentiated (Table 3).

5. Subsurface drainage and vertical seepage (D) may be significant in soils with excessive draining properties. On poorly to well-drained soils, subsurface flow and vertical seepage could be modest or nonexistent. Table 2 presents potential estimates of the drainage rate as a percentage of the precipitation rate, under a variety of conditions.

6. Surface runoff (RO), in general, may be the most important part of precipitation water. However, a distinction should be made between steeply sloping and level ground (Table 2). The latter situation corresponds mostly to poorly drained areas, but level ground may allow substantial vertical drainage if the soil zone is thick and coarse grained. If subsurface drainage is good, the water table is deep, and the soil is not wet, the D term will be significant—15 to 25% of the precipitation term—after a storm not exceeding 25 mm of precipitation per 24 hours. On excessively drained soil, after full saturation, runoff may become significant [RO = (0.40...0.60) P] under a combination of heavy rainfall (more than 25 mm/24 hours) and steep land (slope greater than 5 to 6%) conditions. Land-cover has its own influence on determining runoff discharges (f < 0.5 for dense vegetation cover; f > 0.5 on sparse vegetation or urbanized environment).

Water-Budget Model

The water-budget factor (F_B) in Equation 4 will assume different forms when associated with different climatic conditions and soil-vegetation patterns over the basin. To allow for easier application of the water-budget model, Equation 4 can be adapted to different seasons. The three seasons assumed for the Napa Basin and presented in Table 4 have been differentiated in terms of one water-deficit criterion, the monthly values of (ET – P). Table 4 also offers one characteristic numerical

Table 4. Set of Characteristic Monthly Water-Budget Equations for a Three-Season Scheme

Case	Season	ET–P (mm)	Typical budget equation	Budget example, mm
ID=1	May–September	> 150	$F_{B1} = IR - ET - D$	$F_{B1} = 240 - 280 - 30$ $(F_{B1} = -70)$
ID=2	October, November, March, April	0 to 150	$F_{B2} = P + IR - ET - RO$	$F_{B2} = 40 + 100 - 140 - 20$ $(F_{B2} = -20)$
ID=3	December–February	< 0	$F_{B3} = P + INF - ET - D - RO$	$F_{B3} = 100 + 20 - 40 - 10 - 40$ $(F_{B3} = +30)$

example for each type of monthly budget equation. Using the drainage-plus-runoff potential pattern described by Soil Conservation Service (1978) and schematized in Figure 2, it is possible to estimate separately and map the F_B values for each of the seasons identified in Table 4. Meteorological data processed in the water-budget equations have been extracted from national and local records (National Climatic Data Center, 1971–1995; Soil Conservation Service, 1978; California Department of Water Resources, 1978).

RESULTS

Figures 3, 4, and 5 provide averaged estimates of the modified de Martonne aridity index I_{Mod} for the three cases (ID = 1, 2, and 3) of the seasonal water-budget equation proposed in Table 4, based on the mapped F_B values and Equations 2 and 3. Those estimates are based on multicriterion data differentiation and analysis, in terms of air-temperature regime, precipitation-deficit condition, irrigation application, subsurface inflow and outflow components, soil drainage potential, land slope and runoff pattern, use of land resources, and vegetation-cover availability. Average ranges of both the modified and classical index values for the Napa Basin by season are compared in Table 5; the characterization is based on the index-class description presented in Table 1.

For ID = 1, 2, and 3 (Tables 4 and 5), a comparative example of de Martonne aridity-index values, differentiated according to four land-use categories, is presented in Figure 6. As shown in Table 5, the largest range of values for the modified index (I_{Mod}) occurs in the warmest season, whereas for the classical form (I_{dM}) it occurs during the most rainy interval. The reason is that the soil-water deficit during the summer can be partly covered through irrigation-water management; the fact that wildland is not irrigated results in an even higher value of the modified index. On the other hand, given that the classical index is not affected by other factors such as evapotranspiration and runoff, its values are influenced mostly by the amount of rainfall—which is highly differentiated during the winter season between the northern mountainous landscape and the southern agricultural environment.

Under drought conditions, as in 1976–1977 (California Department of Water Resources, 1978) and 1987–1992 (California Department of Water Resources, 1994), average values of the modified de Martonne index throughout the Napa

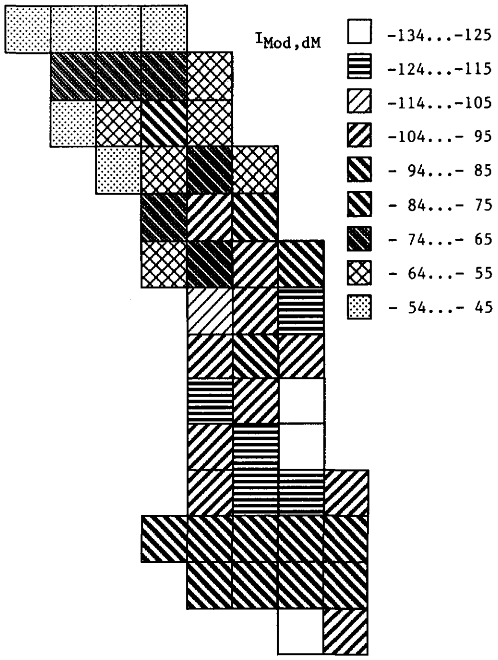

Fig. 3. Modified de Martonne aridity index average for May to September.

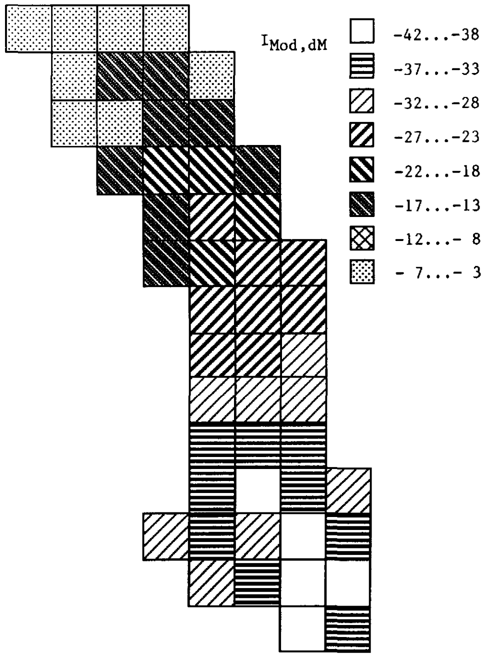

Fig. 4. Modified de Martonne aridity index average for March, April, October, and November.

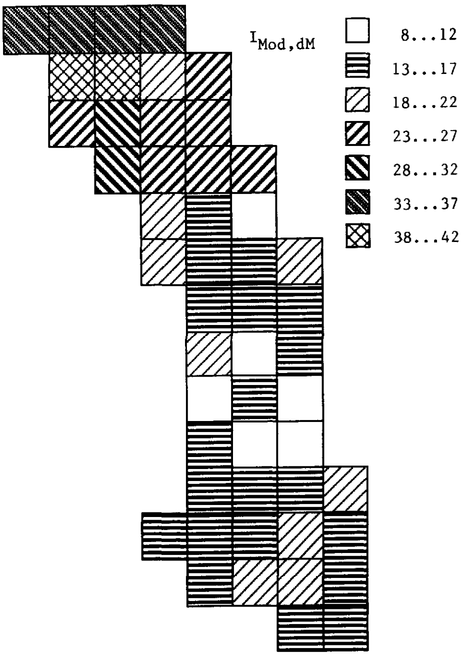

Fig. 5. Modified de Martonne aridity index average for December to February.

Table 5. Comparative I_{Mod} versus I_{dM} Range and Character of Climate in the Napa Basin

Case	I_{Mod} range	Character of climate	I_{dM} range	Character of climate
ID=1	−135 to −45	Excessively dry	+1 to +10	Dry
ID=2	−40 to −5	Very dry	+25 to +50	Wet to very wet
ID=3	+10 to +40	Intermediate to wet	+85 to +130	Abundantly wet

Basin have been found to be 20 to 40% higher than in the multiyear period 1958–1995. During May–September 1976, for example, the I_{Mod} average values ranged between −70 and −170, whereas the I_{dM} ones remained within the interval 0.2 to 4.0. Although much more elaborate than the de Martonne index, the PDSI to some extent suffers from the same deficiency of limiting the most severe drought occurrences to the minimum values of −6 or −7 (Alley, 1984; Wilhite and Rhodes, 1994).

Thus, the earlier de Martonne aridity index fails to identify extreme meteorological events with the same level of precision as that of the modified index. Information provided by the modified index, therefore, is more useful in characterizing severe droughts because there is no fixed minimum threshold for the hydroclimatic deficit. In similar fashion, the modified index also can identify hydrological excess, a major issue of water agencies concerned with flood control.

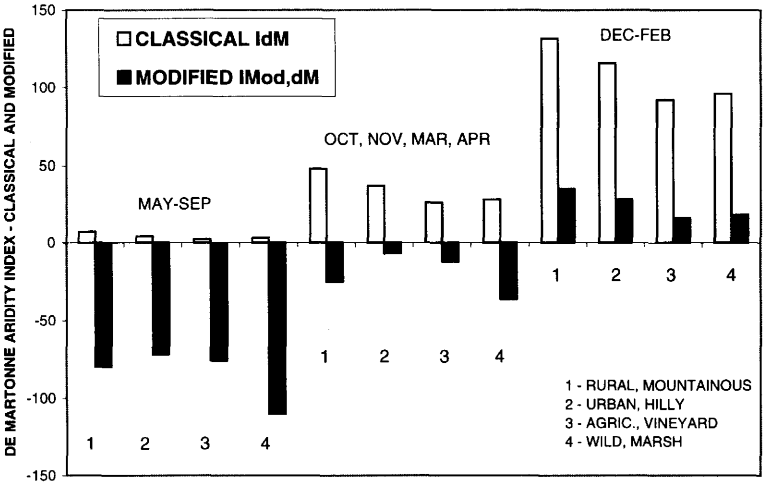

Fig. 6. Variation of the de Martonne aridity index, modified versus classical, in the three seasonal and four land categories.

CONCLUSIONS

The modified de Martonne aridity index offers a simple method for distinguishing vulnerability to drought under various geographical conditions. When compared to the classical de Martonne aridity index, the modified index proposed in this paper takes into account a water-budget equation in addition to the precipitation rate. Therefore, whereas the classical index could have positive values or at least ones around zero, the new index may yield significant negative values for California during the period from March through November.

The geographical condition of the Napa Basin has been differentiated on the basis of a multicriterion investigation—of air temperature, precipitation deficit, irrigation application, subsurface inflow and outflow, soil drainage, slope and runoff, land use, and vegetation cover. The diversity of I_{Mod} values illustrates this differentiation. From this investigation, parts of the study area could be ranked as only moderately wet even during the most rainy period of the year (December–February). Furthermore, in spring and fall, according to the classical de Martonne index, the climatic character on the Napa Basin appears to be wet to very wet, but by considering the modified index values, its climatic regime could be ranked as very dry.

Unlike the Palmer drought severity index, widely used in the United States to rank the potential impacts of droughts, the modified de Martonne aridity index allows for easier estimation. Its values can be associated both with seasonal change in meteorological conditions and with differentiation within the geographical landscape. The proposed approach can be used in other locations by simply adapting the water-budget equation to different environments. This may be effected through re-quantifying certain coefficients (*a* through *f*), considering new factors (such as the contribution of capillarity, in the case of shallow ground water), or ignoring other factors already considered in the water budget (e.g., irrigation). There is as yet insufficient study to prove that over long intervals the modified index is more useful than the PDSI for indicating extreme meteorological conditions. It is obvious, however, that calculation of the modified de Martonne index is expeditious and offers new insights with respect to any type of landscape. Use of this new approach might help institutional decision makers to allocate funds more effectively for drought prevention and alleviation programs.

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