College of Soil Physics

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Aridity and drought indices

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ARIDITY AND DROUGHT INDICES

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Why aridity indices???

To delineate zones prone to **desertification**
Those areas characterized by **low rainfall** and by **high summer temperatures**, so that the vegetation has little opportunity to restore after destruction by **human impact** or prolonged **droughts**.

---- desertification???
---- aridity???
---- droughts???
The Earth Summit (UNCED, Rio de Janeiro, 1992) defined and The General Assembly of UN (UNCED, Paris, 1994) approved the definition of DESERTIFICATION:

"Desertification is land degradation in arid, semi-arid and dry sub-humid areas resulting from climatic variations and human activities’
DESER TIFICATION = drylands

- Drylands = arid, semi-arid, (dry)sub-humid
- 40% of earth’s surface
- 20% of earth’s population
- Drylands are susceptible to ‘human-induced soil degradation’ and ‘degradation of vegetation’
Global extent of desertification

3 assessments
(mainly for political reasons)
Map 1/25.000.000 by FAO, UNESCO, WMO

1. UNCOD (1977):

United Nations Conference on Desertification

Total area susceptible to desertification: 5281 Mha
Total area affected by desertification: 3970 Mha
Global extent of desertification

2. GAP I (1984):
General Assessment of Progress
(Plan of action to combat desertification)

questionnaire to 91 countries → failure
UNEP used consultants

Distinction between: rainfed & irrigated cropland
rangeland

STILL NO METHODOLOGY!!!!!!!!!
Global extent of desertification

3. GAP II (1992)

Used the Soil Data Base of GLASOD
(Global Assessment of Soil Degradation)

Human induced soil degradation:
- Degraded irrigated lands: 43 Mha
- Degraded rainfed croplands: 216 Mha
- Degraded rangelands: 757 Mha

Rangelands with degraded vegetation: 2576 Mha

Total: 3592 Mha
Global extent of desertification

- Example of Africa

  - 16% of surface: water erosion
  - 45% of surface: wind erosion
  - 25% of surface: salinisation
  - 61% of surface: animal pressure
  - 45% of surface: population pressure
ARIDITY VERSUS DROUGHT

- **ARIDITY**

  *Permanent* pluviometric deficit
  (long-term climatic phenomenon)

  Linked to specific climatic data:
  - strong insolation
  - elevated temperatures
  - low air humidity
  - strong evapotranspiration
**ARIDITY VERSUS DROUGHT**

- **DROUGHT**
  - *Temporary* pluviometric deficit
  - (short-term phenomenon)
  - Below **average** availability of natural water
    - **Physical aspect:** below the long-term mean (normal)
    - **Social aspect:** below expected volume to satisfy needs for agriculture, livestock, domestic use

  DROUGHT is also:
  - annual/seasonal/monthly rainfall less than normal
  - reduced river flow

  DESERTIFICATION is commonly related to DROUGHT
Drylands are affected in an irregular manner by droughts.

**Types of drought**
- meteorological drought
- hydrological drought
- agricultural drought
- edaphic drought
Meteorological drought

- Annual precipitation < average for one or several successive years
  
  example: Sahel 1960s, 1970s, 1980s

**BUT!!!** Average is misleading because rain can be scattered or dry periods can alternate with periods of excessive rains.
Hydrological drought

- Water resources used for industry, human, and animal consumption or support of agriculture (irrigation) is low.
Agricultural drought

- Related to rainfed agriculture
- Related to soil moisture deficit during growing season

Soil moisture deficit can be determined by:
- precipitation
- PET
- soil moisture
- crop coefficient (moisture requirements)

Absolute annual or seasonal deficit of precipitation is not a good indicator
better: rainfall distribution
Edaphic drought

- Decrease of infiltrability of the soil
- Increase in runoff and erosion
DELINEATING ARIDITY ZONES

Based on INDEX OF MOISTURE DEFICIT

or

ARIDITY INDEX $\text{AI} = \frac{P}{\text{PET}}$
DETERMINATION OF PET

1) direct measurements using lysimeters
   NO STANDARDIZATION

2) empirical formulas
   Penman & Penman Monteith
   NEEDS LOT OF DATA: solar radiation, wind velocity, relative humidity, temperature

3) relation between measured PET and two parameters
   ex. Thornthwaite: mean monthly temperature and average number of daylight-hours/month
   OVERESTIMATES PET FOR DRY CONDITIONS
   UNDERESTIMATES PET FOR MOIST AND COLD CONDITIONS
## Global Extent of Aridity Zones

<table>
<thead>
<tr>
<th>Aridity Index</th>
<th>Million (ha)</th>
<th>% World Land Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold (&gt; 0.65)</td>
<td>1765.0</td>
<td>13.6</td>
</tr>
<tr>
<td>Humid (&gt; 0.65)</td>
<td>5100.4</td>
<td>39.2</td>
</tr>
<tr>
<td>Dry sub-humid (0.50-0.65)</td>
<td>1294.7</td>
<td>9.9</td>
</tr>
<tr>
<td>Semi-arid (0.20-0.50)</td>
<td>2305.3</td>
<td>17.7</td>
</tr>
<tr>
<td>Arid (0.05-0.20)</td>
<td>1569.1</td>
<td>12.1</td>
</tr>
<tr>
<td>Hyper-arid (&lt; 0.05)</td>
<td>978.2</td>
<td>7.5</td>
</tr>
<tr>
<td>Drylands (3+4+5+6) (&lt; 0.65)</td>
<td>6147.3</td>
<td>47.2</td>
</tr>
<tr>
<td>Susceptible Drylands (3+4+5) (0.05-0.65)</td>
<td>5169.1</td>
<td>39.7</td>
</tr>
</tbody>
</table>
## World drylands (Mha)

<table>
<thead>
<tr>
<th></th>
<th>Africa</th>
<th>Asia</th>
<th>Australia</th>
<th>Europe</th>
<th>North America</th>
<th>South America</th>
<th>World Total</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hyper - arid</td>
<td>672</td>
<td>277</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>26</td>
<td>978</td>
<td>16</td>
</tr>
<tr>
<td>Arid</td>
<td>504</td>
<td>626</td>
<td>303</td>
<td>11</td>
<td>82</td>
<td>45</td>
<td>1571</td>
<td>26</td>
</tr>
<tr>
<td>Semi-arid</td>
<td>514</td>
<td>693</td>
<td>309</td>
<td>105</td>
<td>419</td>
<td>265</td>
<td>2305</td>
<td>37</td>
</tr>
<tr>
<td>Dry sub-humid</td>
<td>269</td>
<td>353</td>
<td>51</td>
<td>184</td>
<td>232</td>
<td>207</td>
<td>1296</td>
<td>21</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1959</strong></td>
<td><strong>1949</strong></td>
<td><strong>663</strong></td>
<td><strong>300</strong></td>
<td><strong>736</strong></td>
<td><strong>543</strong></td>
<td><strong>6150</strong></td>
<td><strong>100</strong></td>
</tr>
<tr>
<td>% World Total</td>
<td>32</td>
<td>32</td>
<td>11</td>
<td>5</td>
<td>12</td>
<td>8</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>% Total Global Land Area</td>
<td>13.1</td>
<td>13.0</td>
<td>4.4</td>
<td>2.0</td>
<td>4.9</td>
<td>3.6</td>
<td>41.0</td>
<td></td>
</tr>
<tr>
<td>% Continent Area</td>
<td>66</td>
<td>46</td>
<td>75</td>
<td>32</td>
<td>34</td>
<td>31</td>
<td>41</td>
<td></td>
</tr>
</tbody>
</table>
DRYLAND ZONES

- Based on climate and environmental attributes
  - BUT!!!! Dryland boundaries are neither static nor abrupt because of:
    1. high inter-annual variability in mean rainfall
    2. occurrence of drought which may last for several years.

- Individual aridity zones do not represent homogeneous climates, either in the long term or during a particular time band.

- Dryland boundaries may not be defined in terms of natural vegetation or soil type because of human induced processes.
DRYLAND ZONES

Hyper-arid zones (environments)
Arid zones
Semi-arid zones
Dry sub-humid zones
Hyper-arid areas

Very limited rainfall
Highly variable rainfall: inter-annually (100%), monthly
Year-long periods without rainfall

true deserts not prone to desertification
very low biological productivity
Arid zones

- < 200 mm in annual winter rainfall
- < 300 mm in summer rainfall
- Inter-annual variability 50-100%
- Pastoralisme is possible
- Use of groundwater is highly susceptible to climate variability
Semi-arid zones

Highly seasonal rainfall distribution
< 500 mm in winter rainfall regimes
< 800 mm in summer rainfall regimes
Inter-annual variability: 25-50%
Grazing of grassland

Sedentary agricultural activities are susceptible to seasonal and inter-annual deficiency
Dry sub-humid zones

High seasonal rainfall regimes
< 25% inter-annual variability
Rainfed agriculture

Susceptible to degradation enhanced by seasonal rainfall, drought periods and increasing intensity of human use.

Dry sub-humid zones are included in the definition of desertification
ARIDITY INDICES

- Problem??

- Data collection
- The more parameters, the more errors
EVALUATION AND CLASSIFICATION OF CLIMATIC INDICES FOR YAZD REGION (IRAN)

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PURPOSE:

- This study aims at comparing different climatic indices for evaluating the aridity and the rain aggressivity and rain distribution based on climatic data from 21 weather stations in the Yazd-Ardakan basin (Iran) and this for 5 to 48 successive years.
Five aridity indices were used to assess the aridity in the basin:

- De Martonne Aridity Index
- Emberger Aridity Index
- UNEP Aridity Index
- Thornthwaite Classification
- Gaussen-Bagnouls Classification.

For rain distribution and rain concentration

- Modified Fournier Index (MFI)
- Precipitation Concentration Index (PCI)
1. Aridity index of De Martonne

\[ I_{\text{DM}} = \frac{P}{t + 10} \]

\( P \) = Annual average rainfall in mm.
\( t \) = Annual average temperature in degrees centigrade.

<table>
<thead>
<tr>
<th>Climate Type</th>
<th>Aridity Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arid</td>
<td>0-10</td>
</tr>
<tr>
<td>Semi-arid</td>
<td>10-20</td>
</tr>
<tr>
<td>Mediterranean</td>
<td>20-24</td>
</tr>
<tr>
<td>Semi-humid</td>
<td>24-28</td>
</tr>
<tr>
<td>Humid</td>
<td>28-35</td>
</tr>
<tr>
<td>Very Humid</td>
<td>35-55</td>
</tr>
<tr>
<td>Extremely Humid</td>
<td>&gt;55</td>
</tr>
</tbody>
</table>

2. Aridity index of Emberger

\[ I_E = \frac{100 \times P}{M^2 - m^2} \]

\( M \) = Average temperature of the hottest month in degrees centigrade.
\( m \) = Average temperature of the coldest month in degrees centigrade.
\( P \) = Annual average rainfall in mm.
3. UNEP aridity index (P/ETP)

- $ETo = 16 \times Nm \times (10 \times Tm / I)^a$
  - $Tm = \text{mean monthly temperature}$
  - $Nm = \text{adjustment factor related to hours of daylight}$
  - Heat Index or $I = \text{Sum} \ (Tm / 5)^{1.514}$ for $m = 1 \ldots 12$
  - $a = 6.75 \times 10^{-7} \times I^3 - 7.71 \times 10^{-5} \times I^2 + 1.792 \times 10^{-2} \times I + 0.49239$

4. Thornthwaite classification

$$PE_{index} = \sum_{1}^{n=12} \left( \frac{P}{T-10} \right)^{10/9}$$

- $P = \text{monthly precipitation in inches}$
- $T = \text{temperature in } ^\circ\text{F}$; and $n = \text{months} = 12$. 
5. Gaussen-Bagnouls classification method

- combination of average monthly temperature and total rainfall
- gives more precise climatic classification
- easily climatic identification by determining separately the numbers of dry and wet months

P > 3T  →  Humid
3T > P > 2T  →  Semi-humid
P < 2T  →  Arid
YAZD RAINFALL MOVING AVERAGE

YEAR

RAINFALL (mm)


Series 1
7 per. Mov. Avg. (Series 1)
61.58
6. Precipitation concentration index

- to estimate the temporal variability of monthly rainfall

\[ PCI = 100 \frac{\sum p_i^2}{P^2} \]

- \( p \) = monthly precipitation
- \( P \) = annual precipitation

<table>
<thead>
<tr>
<th>PCI</th>
<th>Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.3 – 10</td>
<td>uniform</td>
</tr>
<tr>
<td>10 – 15</td>
<td>Moderately seasonal</td>
</tr>
<tr>
<td>15 – 20</td>
<td>seasonal</td>
</tr>
<tr>
<td>20 – 50</td>
<td>Highly seasonal</td>
</tr>
<tr>
<td>50 – 100</td>
<td>Irregular</td>
</tr>
<tr>
<td>Station</td>
<td>PCI1</td>
</tr>
<tr>
<td>-------------------</td>
<td>-------</td>
</tr>
<tr>
<td>ABARKUH</td>
<td>29.87</td>
</tr>
<tr>
<td>ARDEKAN</td>
<td>28.36</td>
</tr>
<tr>
<td>ASHKZAR</td>
<td>24.98</td>
</tr>
<tr>
<td>BAJGAN</td>
<td>26.66</td>
</tr>
<tr>
<td>DEHSHIR</td>
<td>26.67</td>
</tr>
<tr>
<td>GHOTROOM</td>
<td>23.87</td>
</tr>
<tr>
<td>HAJIABAD</td>
<td>26.66</td>
</tr>
<tr>
<td>KHAHARANAGH</td>
<td>22.05</td>
</tr>
<tr>
<td>KHOOR BIABANAK</td>
<td>28.43</td>
</tr>
<tr>
<td>MAZRAEH NOW</td>
<td>28.21</td>
</tr>
<tr>
<td>NASRABAD</td>
<td>21.01</td>
</tr>
<tr>
<td>ROBATPOSHTE</td>
<td>25.15</td>
</tr>
<tr>
<td>TAFT</td>
<td>23.57</td>
</tr>
<tr>
<td>VARZANEH</td>
<td>28.21</td>
</tr>
<tr>
<td>ANAR</td>
<td>29.64</td>
</tr>
<tr>
<td>BAFGH</td>
<td>30.15</td>
</tr>
<tr>
<td>HOJATAABAD</td>
<td>21.33</td>
</tr>
<tr>
<td>KAVIR SIYAHKOOGH</td>
<td>31.59</td>
</tr>
<tr>
<td>SAGHAND</td>
<td>28.23</td>
</tr>
<tr>
<td>YAZD</td>
<td>29.80</td>
</tr>
</tbody>
</table>
Dry and humid periods

\[ LP_D = \text{N° of dry months} = P < 0.5 \ ET_0 \]

\[ LP_R = \text{N° of rainy months} = P > 0.5 \ ET_0 \]

where: \( LP_D \): length of the water shortage period
\( LP_R \): length of the water surplus period

Water shortage

\[ DH = \sum_{1}^{12} (P - ET_0) \]

DH = yearly water shortage (mm)
P = monthly precipitation (mm)
MAP of Aridity Zones in Latin America

Project CAZALAC
(Centro del Agua para Zonas Áridas y Semiáridas de América Latina y El Caribe), La Serena, Chili
Penman-Monteith-FAO

Characteristics of a hypothetical reference crop
(green grass of 0.12 m high with an albedo of 0.23)

\[ r_a = \frac{208}{u_2} \text{ s/m} \]

\[ \alpha R_s = 0.23 R_s \]

\[ r_s = 70 \text{ s/m} \]

\[ T_m, \text{ monthly mean temperature (°C)} \]
\[ RS, \text{ solar radiation in cal cm}^{-2} \text{ d}^{-1} \]
\[ HR, \text{ monthly mean relative humidity (%)} \]
\[ U_2, \text{ wind speed in m s}^{-1} \]

\[ r_a : \text{ aerodynamic resistance} \]
\[ r_s : \text{ surface resistance of the green grass} = 70 \text{ s/m} \]
Penman-Montheith-FAO

\[
ET_0 = \frac{0.408\Delta(R_n - G) + 900}{T + 273} \frac{u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}
\]

Where:
- \( ET_0 \) baseline evapotranspiration [mm day\(^{-1}\)],
- \( R_n \) net radiation on the crop surface [MJ m\(^{-2}\) day\(^{-1}\)],
- \( G \) heat flow density in the soil [MJ m\(^{-2}\) day\(^{-1}\)],
- \( T \) average daily temperature at a 2 m height [°C],
- \( u_2 \) wind speed at a 2 m height [m s\(^{-1}\)],
- \( e_s \) saturation vapor pressure [kPa],
- \( e_a \) current vapor pressure [kPa],
- \( e_s - e_a \) saturation vapor pressure gap [kPa],
- \( \Delta \) slope of the saturation vapor pressure line in function of temperature [kPa °C\(^{-1}\)],
- \( \gamma \) psychrometric coefficient [kPa °C\(^{-1}\)].
Protocol to calculate the baseline Evapotranspiration by using the FAO/Penman-Monteith equation

Step 1. Calculation of Net Radiation, Rn (MJ/m² day) from global solar radiation, RG (Cal/cm² day)

\[ R_n = R_G \times 0.0419 \times 0.8 \]

Factor 0.0419 converts cal/cm² day into MJ/m² day
Factor 0.8 is the Rn/RG quotient for a vegetated area with a good water supply

Step 2. Calculation of air vapor pressure at saturation, es (kPa)

\[ es = 0.707 \times \exp(0.05979 \times T_a) \]
Ta is the average air temperature (°C)

Step 3. Calculation of air saturation shortage Ds(kPa)

\[ D_s = es \times (1 - HR/100) \]
HR is relative humidity in %
Step 4. Calculation of the saturation vapor pressure curve slope, \( \Delta \) (kPa/°C)

\[
\text{TETA} = (T_a + 237.3)^2
\]

\[
\text{ALFA} = 17.27 \times T_a / (T_a + 237.3)
\]

\[
\Delta = 4098 \times (.6108 \times \text{EXP}(\text{ALFA})) / \text{TETA}
\]

Step 5. Calculation of advective contribution

\[
\text{Adv} = (\gamma \times 900 \times U \times D_s) / (T_a + 273)
\]

\( \gamma = .066 \) (kPa/°C)

\( U = \) wind speed in m/s

\( D_s = \) saturation shortage (kPa)

Step 6. Calculation of the radioactive contribution

\[
\text{Rad} = 0.408 \times \Delta \times R_n
\]

Step 7. Calculation of denominator (resistance to vapor diffusion in the limit layer)

\[
\text{Dn} = \Delta + .066 \times (1 + .34 \times U)
\]
Step 8. Calculation of the radioactive component of ETo
   \[ \text{ETRAD} = \frac{\text{Rad}}{\text{Dn}} \]

Step 9. Calculation of the advective component of ETo
   \[ \text{ETADV} = \frac{\text{Adv}}{\text{Dn}} \]

Step 10. Calculation of ETo
   \[ \text{ETO} = \text{ETRAD} + \text{ETADV} \]