Water Resources Engineering and Management

(CIVIL-466, A.Y. 2024-2025)

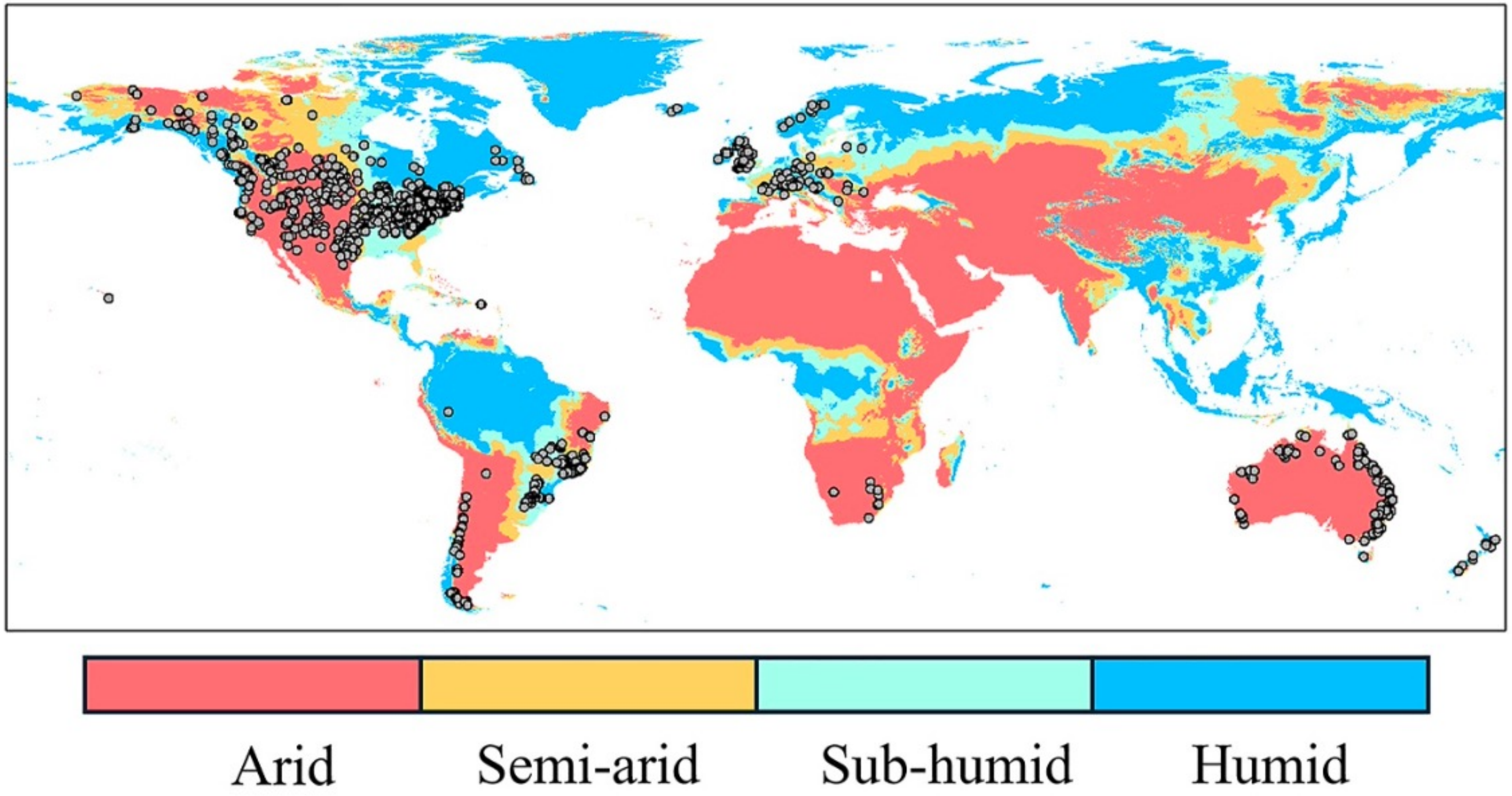
5 ETCS, Master course

Prof. P. Perona
Platform of hydraulic constructions

Lecture 11-2: A prime about droughts and water security

Droughts: definition, analysis and properties

World distribution of arid vs humid regions



Global dryness zones are defined according to their aridity index (*EP/P)*:

(a) Arid (*EP/P* > 1.35);
(b) (b) Semi-arid (1 > *EP/P* < 1.35);
(c) (c) Sub-humid (0.76 > *EP/P* < 1);
(d) (d) Humid (*EP/P* < 0.76)

Xiong et al., WRR, 2025

How to define a drought

Droughts are a **complex phenomenon**, the definition of which is difficult and requires to consider **climate**, **water** and **vegetation** issues

⇩

A first discrimination is based on the *temporal character* of the phenomenon:

- ***drought*** is a *temporary* reduction of *water* resources availibility
- ***aridity*** is *permanent climatic* condition with low seasonal or annual precipitation and high evapotranspiration
- ***desertification*** is a *long term* and *irreversible* process of decrease or destruction of *biological soil* potential due to climatic and human activities factors (drought events can play an accelerating role)

[www.rcdnet.org/drought.php]

DROUGHTS: processes involved and propagatory effect

PLATEFORME DE CONSTRUCTIONS HYDRAULIQUES

Meteorological drought :

Temporal reduction or precip during a prolonged period (precipitation deficit) caused by atmospheric fluctuations related to earth, ecosphere and solar processes.

Agricultural drought :

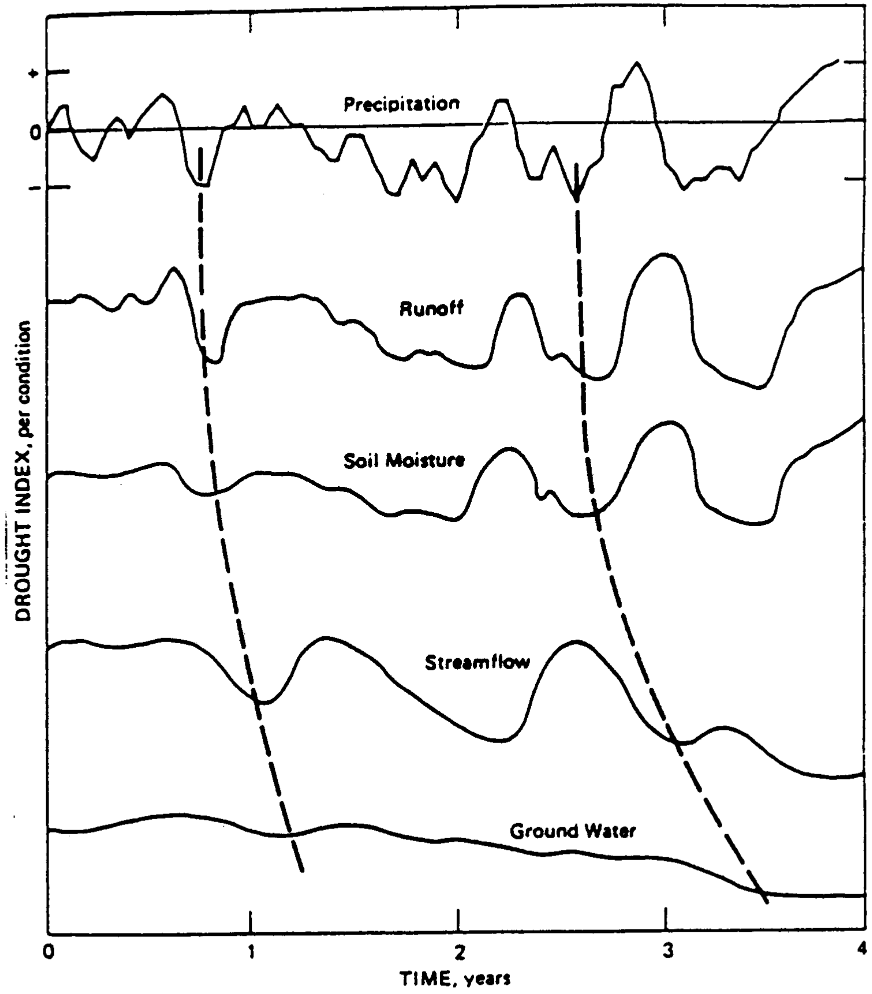
soil moisture deficit deriving from meteorological drought routed trough soil storage mechanism (with time delay and change in amount)

Hydrological drought :

surface flow deficit and groundwater deficit deriving respectively from precipitation deficit and soil moisture deficit routed trough the storage mechanism in natural water bodies

Water Resources (socio-economical) drought :

water supply shortage (drought output) influenced by artificial storage features (reservoir capacity and operation rules) and by different drought mitigation measures



from Rasmusson et al., (1993)

Courtesy of A. Cancelliere, 2009

Droughts: process scheme and the illogical cycle

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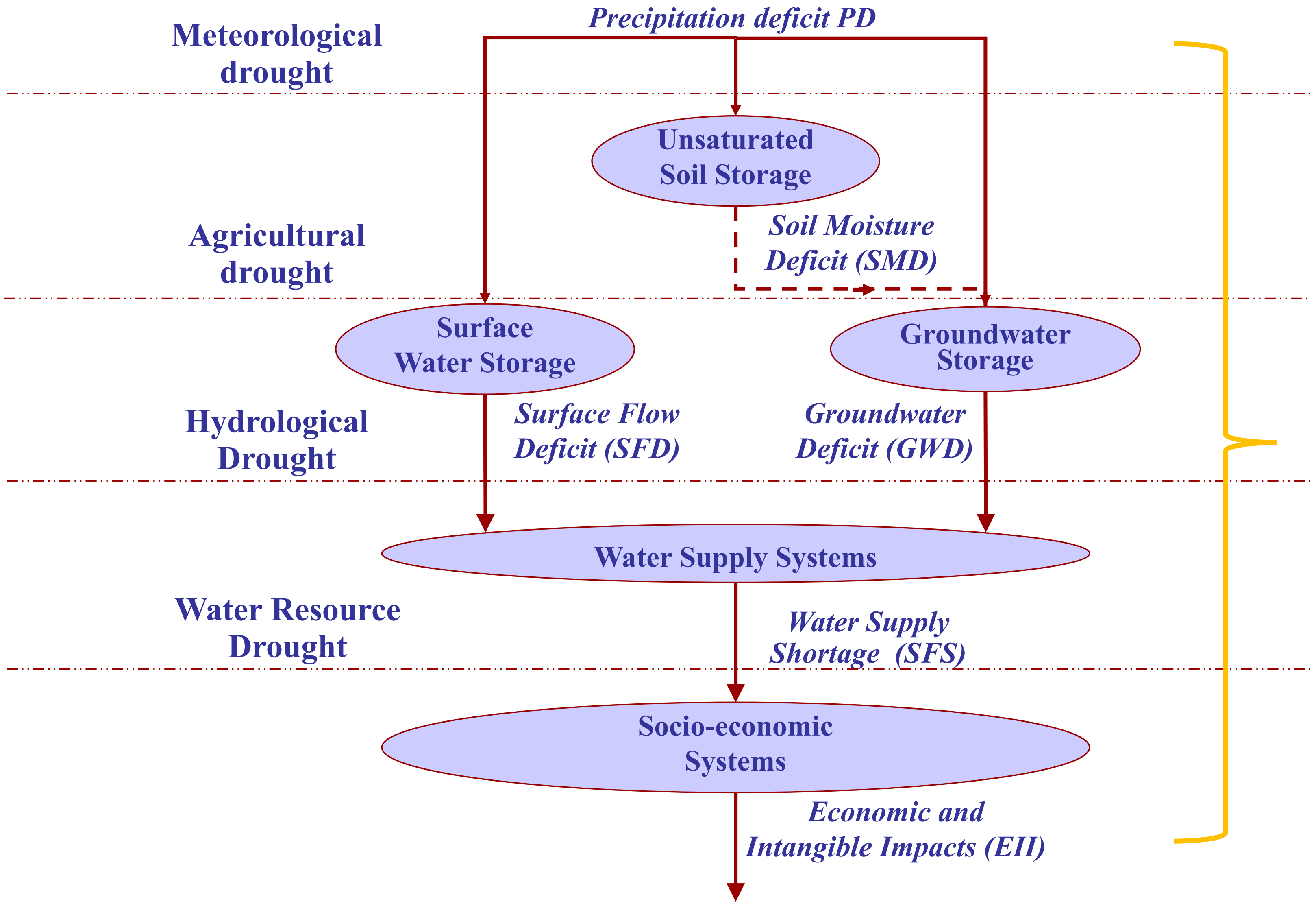
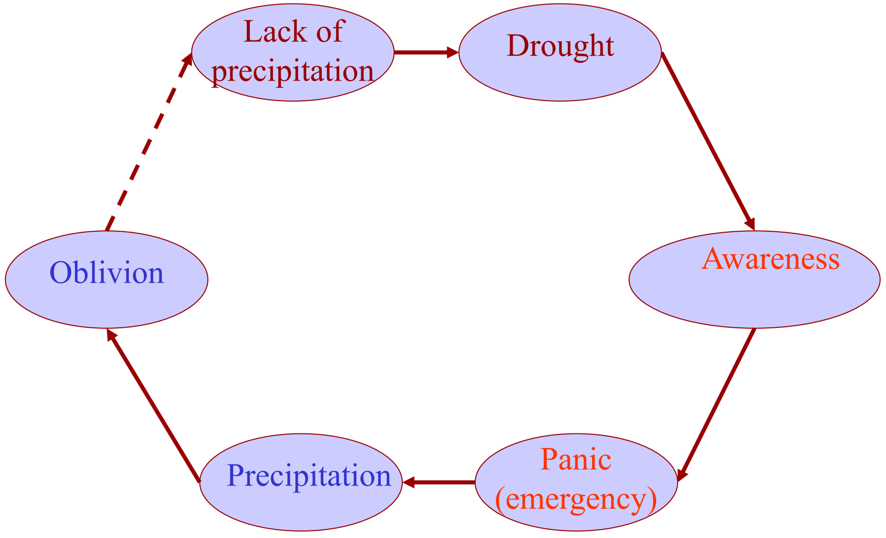


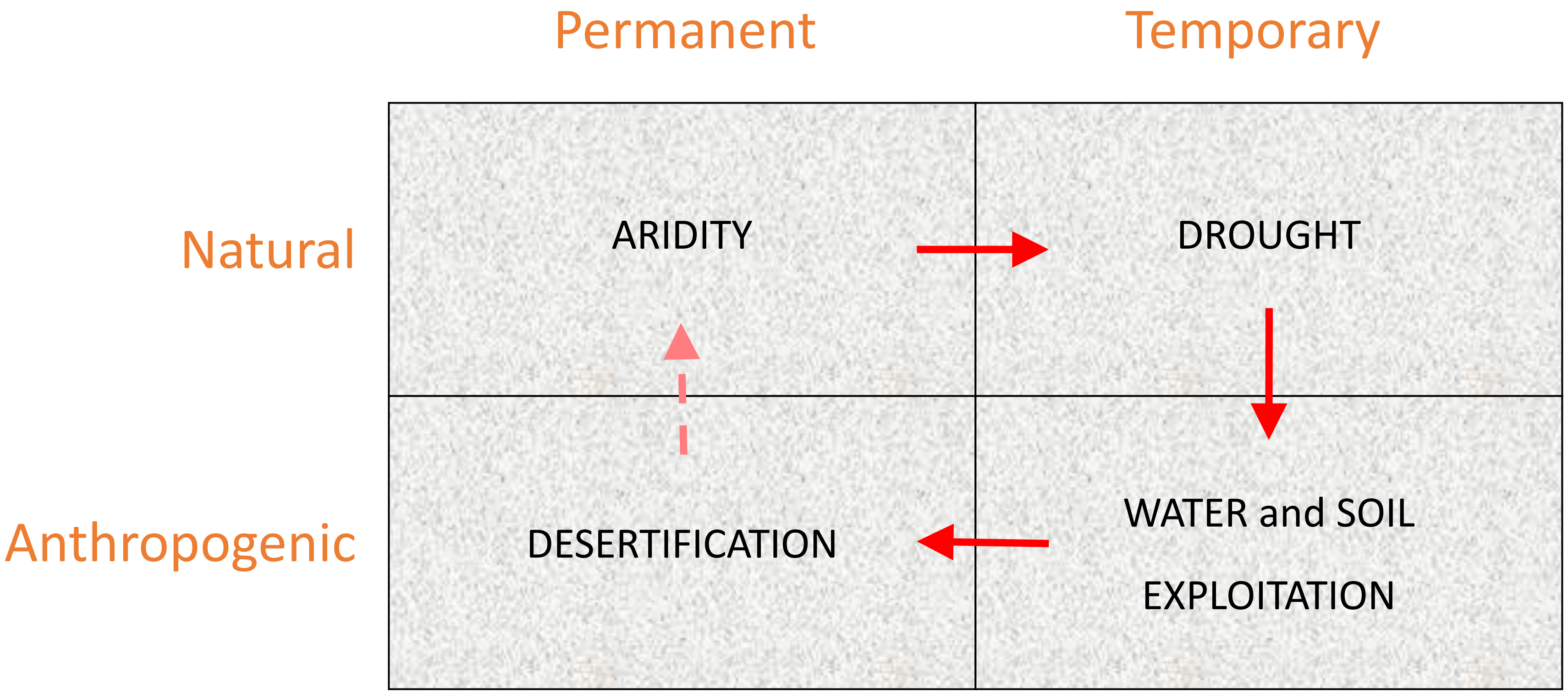
The illogical cycle affecting emergencies



Courtesy of A. Cancelliere, 2009

Drought vs aridity vs desertification

origin, evolution and interdependence



nature induced temporary phenomena can be turned into permanent states by anthropogenic forcings

Drought identification

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The characterization of a drought is done with respect to

- its ***severity/intensity***
- and its ***temporal and spatial extent***

Simple methods

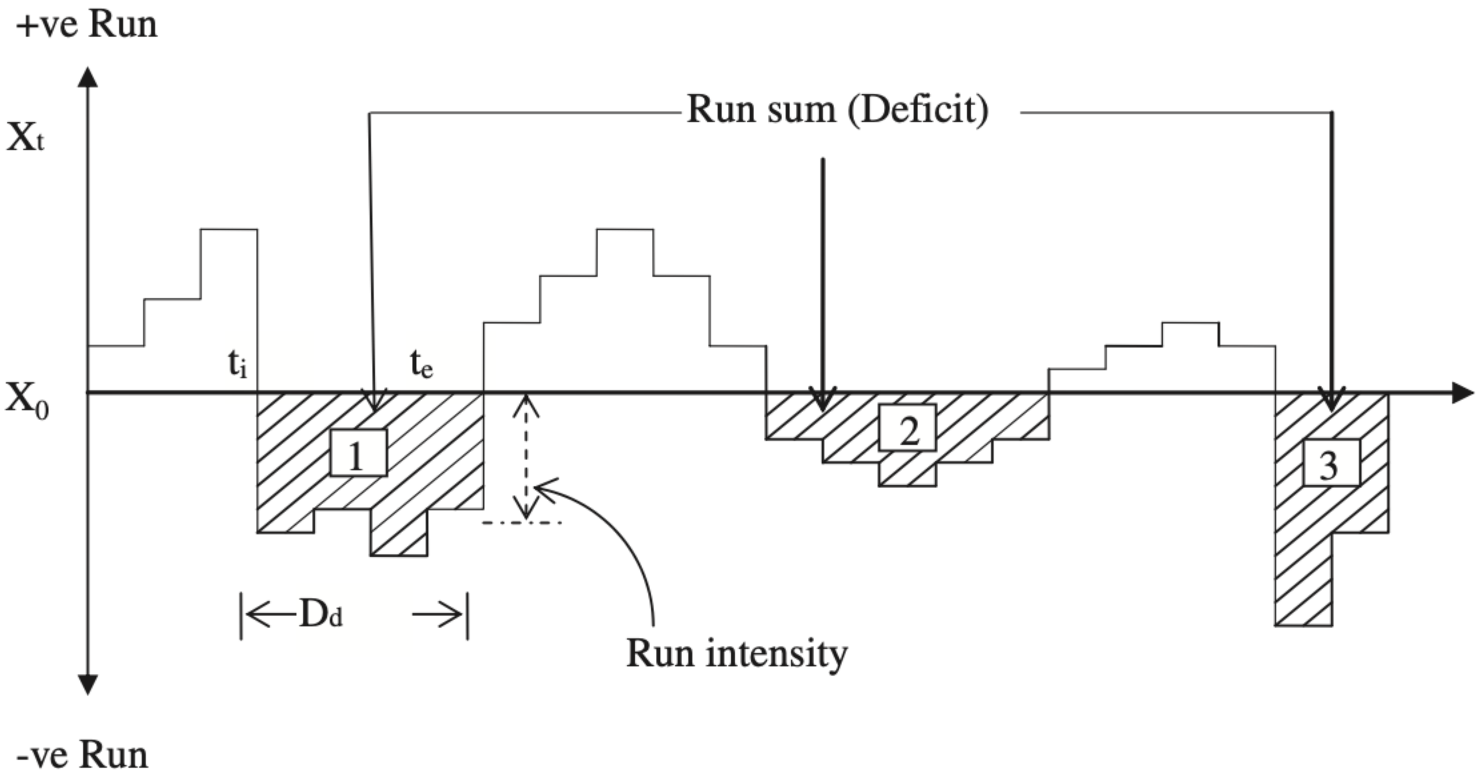
are based on the analysis of **selected components of the hydrologic cycle** and focus only on the intensity

↳ Single component (e.g. precipitation or runoff). In general, a drought occurs when the percentage of cumulated values or quantiles is below a fixed threshold

↳ Multiple components for water balance (e.g. Palmer, SPI, ...). We focus a bit more on these…

Drought identification: the run method

A run is defined as a portion of time series of drought variable X_t, in which all values are either below or above the selected truncation level of X_0



1. Drought with the highest severity;
2. Drought with the longest duration;
3. Drought with the highest intensity

Mishra and Singh, JoH, 2010

Drought event major' components (Dracup et al., 1980:

(a) Drought initiation time (t_i): it is the starting of the water shortage period, which indicates the beginning of a drought.
(b) (b) Drought termination time (t_e): it is the time when the water shortage becomes sufficiently small so that drought conditions no longer persist.
(c) Drought duration (D_d): it is expressed in years/months/weeks, etc., during which a drought parameter is continuously below the critical level. In other words, it is the time period between the initiation and termi- nation of a drought.
(d) Drought severity (S_d): it indicates a cumulative deficiency of a drought parameter below the critical level.
(e) Drought intensity (I_d): it is the average value of a drought parameter below the critical level. It is measured as the drought severity divided by the duration.

Drought identification: multiple-components methods

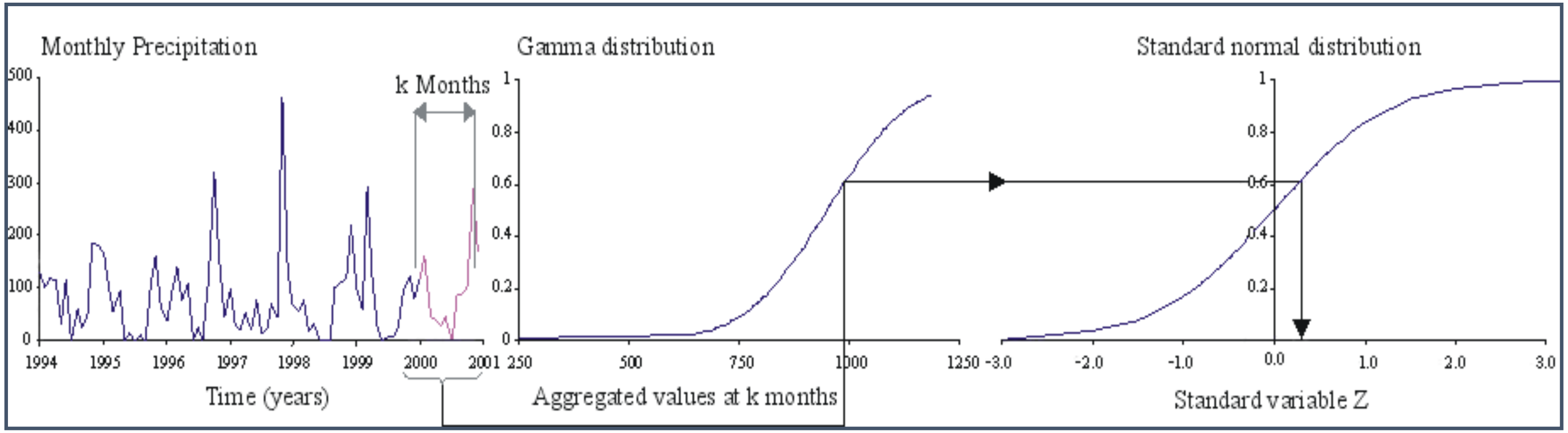
PRECIPITATION BASED INDICES – The Standardized Precipitation Index (SPI)

[McKee et al. 1993]

BACKGROUND: assume **each component of water resources systems reacts to a deficit in precipitation over different time scales** (McKee et al., 1993), e.g. *soil moisture (short time response), streamflow, stored volumes in reservoirs and groundwater (long time scale reaction);*

METHODOLOGY:*;*

Given the time series of a drought variable → Fit a distribution on the cumulated variable aggregated at k months → the value of the standard normal variable corresponding to the computed probability for actual cumulated precipitation is adopted as SPI.



To account for the different time scales, the index is **computed** on cumulated values of precipitation **over various time periods** (k=3, 6, 9, 12, 24, 48 months).

PRECIPITATION BASED INDICES – The Standardized Precipitation Index (SPI)

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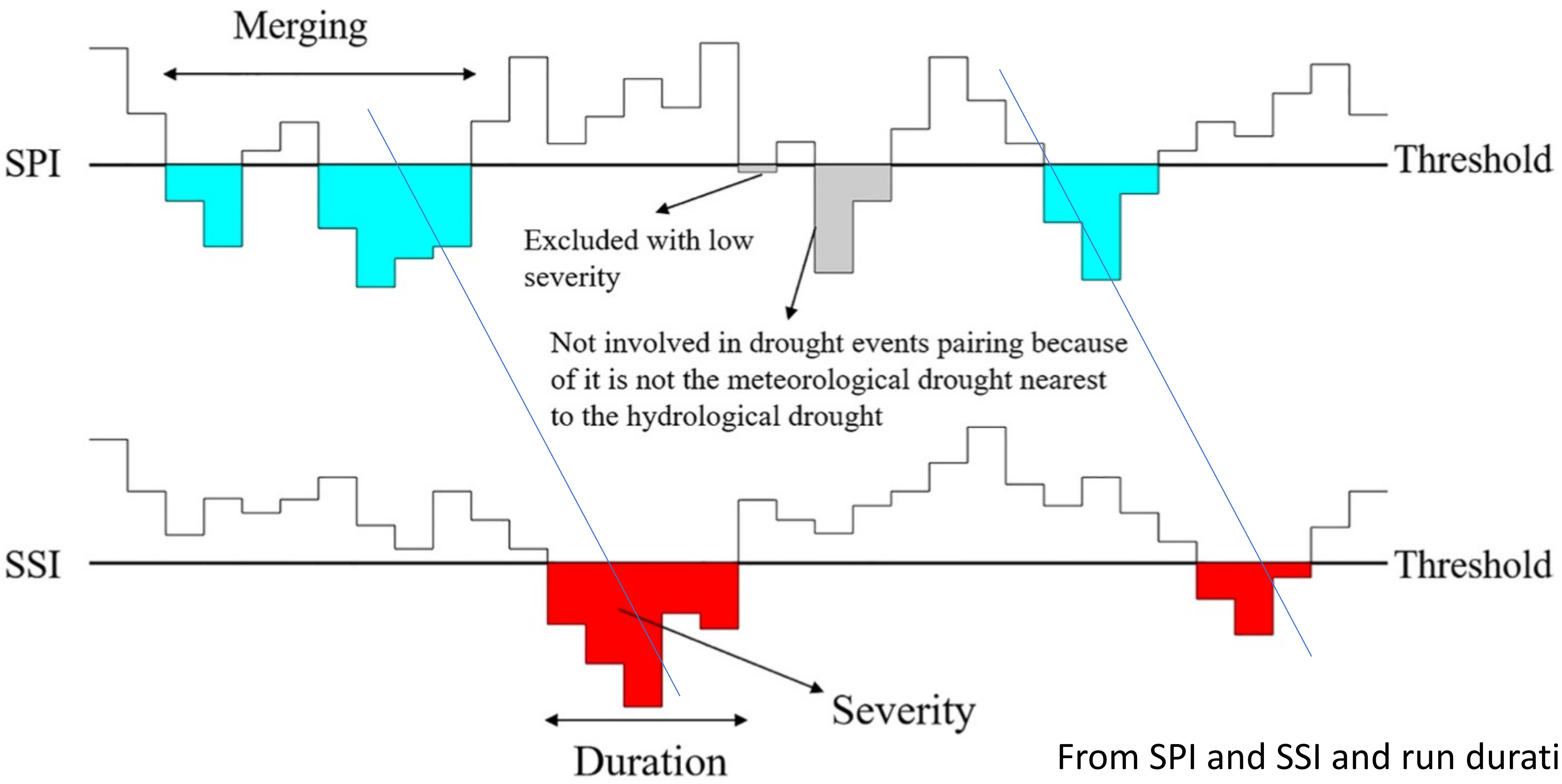
Overview: The SPI is an index based on the probability of precipitation for any time scale.
Who uses it: many drought planners appreciate the SPI's versatility
Pros: the SPI can be computed for different time scales, can provide early warning of drought and help assess drought severity, and is less complex than the Palmer
Drought comparison among different sites
Cons: values based on preliminary data may change

SPI Z	Class
$Z \geq 2.00$	Extremely wet
$1.50 \leq Z < 2.00$	Very wet
$1.00 \leq Z < 1.50$	Moderately wet
$-1.00 \leq Z < 1.00$	Near normal
$-1.50 \leq Z < -1.00$	Moderately dry
$-2.00 \leq Z < -1.50$	Severely dry
$Z \leq -2.00$	Extremely dry

Because the SPI is normalized, wetter and drier climates can be represented in the same way, and wet periods can also be monitored using the SPI.

Similarly, following the same procedure for streamflows, one can derive the Standardized Streamflow Index (SSI)

Drought propagation example



From SPI and SSI and run duration and intensity one can calculate the propagation ratio from meteorological to hydrological droughts, which may enhance how storage determines "memory"

Xiong et al., WRR, 2025

WATER BALANCE INDICES – The Palmer Hydrological Drought Index

It is based on a ***monthly water balance*** considering a simple two-layer soil and expressing moisture conditions in a standardised form.

It is computed for each month *i* by a recursive equation:

$$PH_i = 0.897 PH_{i-1} + \frac{Z_i}{3}$$

where $i = 12(y-1)+j \qquad j = 1, \ldots 12 \qquad y = 1, \ldots n$

and $$Z_i = \left(P_i - \hat{P}_i\right) K_j$$

being:

- Z_i = difference between the actual precipitation P_i and the precipitation $\hat{P}_i$ required to maintain the average supply over the area (Climatically Appropriate Moisture Supply),
- K_j = monthly standardization factor

The Palmer Hydrological Drought Index (cont'd/2)

$\hat{P}_i$ = is the weighted sum of:

- potential evapotranspiration PE_i
- potential recharge of soil moisture PR_i
- potential runoff PRO_i
- potential soil moisture loss PL_i

$$\hat{P}_i = \alpha_j PE_i + \beta_j PR_i + \gamma_j PRO_i - \delta_j PL_i$$

and the weighting factors are function of the monthly average values of the terms of the soil water balance over the calibration period, i.e.

$$\alpha_j = \frac{\overline{ET}_j}{\overline{PE}_j}; \quad \beta_i = \frac{\overline{R}_j}{\overline{PR}_j}; \quad \gamma_1 = \frac{\overline{RO}_j}{\overline{PRO}_j}; \quad \delta_j = \frac{\overline{L}_j}{\overline{PL}_j}$$

The Palmer Hydrological Drought Index (cont'd/3)

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The PHDI is used in a standardised form on a scale ranging from 6 to -6. The drought classification is:

Palmer Index			Drought category
0.49	to	-0.49	Near normal condition
-0.50	to	-0.99	Incipient dry spell
-1.00	to	-1.99	Mild drought
-2.00	to	-2.99	Moderate drought
-3.00	to	3.99	Severe drought
-4.00	or	less	Extreme drought

Effectiveness of Palmer Index for identification and characterisation of hydrological droughts has been questioned. Main **limitations** include:

- *basic hypotheses on the soil water balance modelling*
- *empirical computation of some coefficients*
- *inadequacy of the original calibration period (too short and not representative).*

The use of the Palmer index in regions where precipitation and runoff present high variability has been also questioned.

http://lwf.ncdc.noaa.gov/oa/climate/research/prelim/drought/zimage.html

Drought vs flow-flow statistics

Different time scale of the phenomena:

↳ days for low flows, months or years for drought events

Low flow analysis aims to assess the annual minimum flows corresponding to a fixed probability or return period

Droughts can span over several years: an adequate time interval for drought analysis cannot be adopted

Drought **return period cannot be assessed by the formula** generally **applied** either **for** flood or **low flow** analysis

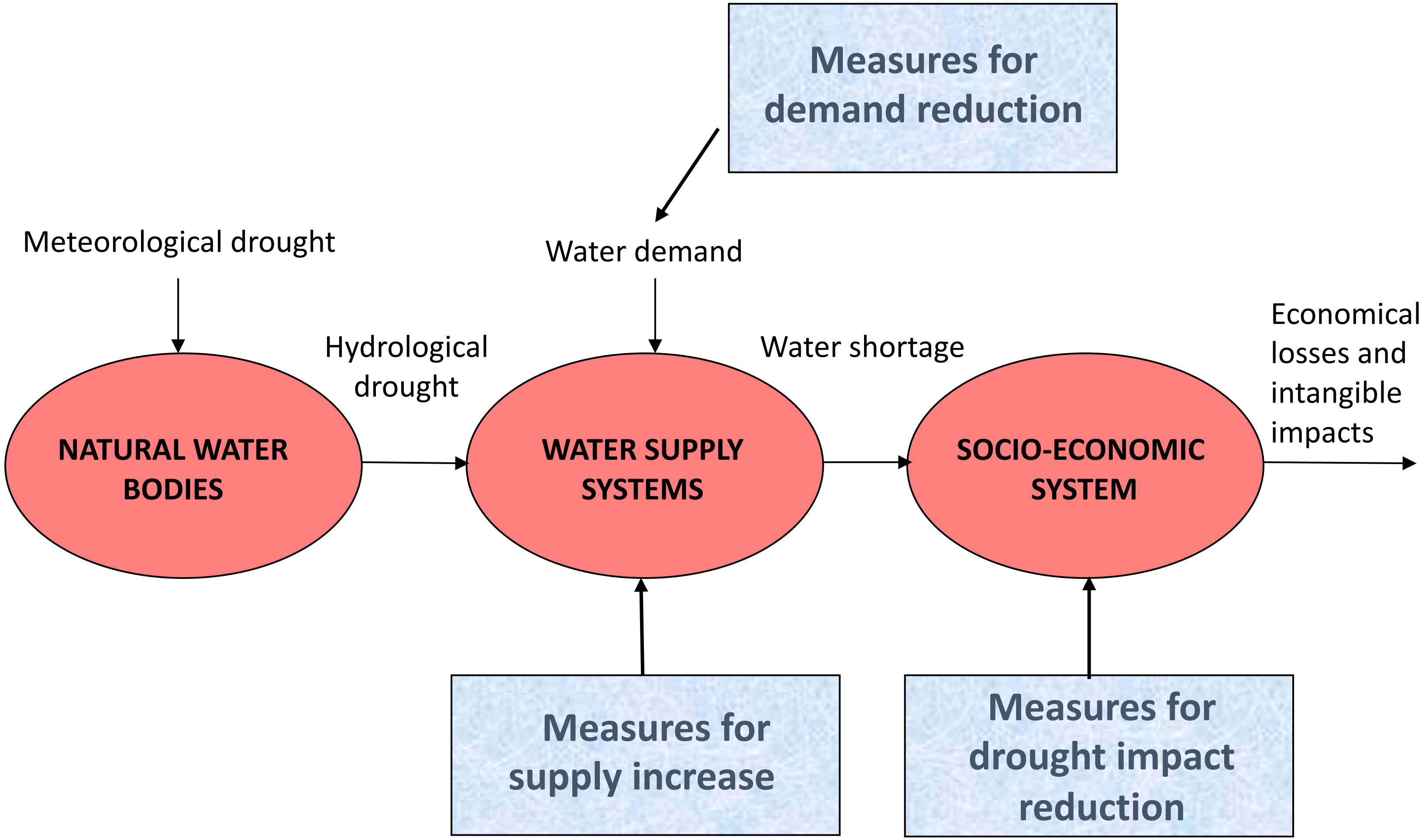
↳

$$T = \frac{1}{P[X_t > x_t]}$$

Drought is a propagating phenomenon occurring over several time scales, whose impact depends on water demand. A new conceptual theory for defining the return period of such phenomena is therefore needed!

Anthropogenic influence and mitigation measures

- A drought is perceived as a natural hazard, but
- A drought is also a ***man-affected phenomenon*** because:
  - *Drought impacts are perceived only when drought affects the life, economic interest or social well being of a human community (there is no drought on oceans!)*
  - *Drought impacts of a certain severity differ according to the ratio of demand to water availability*
  - *Drought impacts can be substantially modified by the strategies adopted for coping with drought risk*



Mitigation measures/actions

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Temporal scales →

	Short-term actions (reactive approach, faces emergency situation and aims at panic attenuation using existing infrastr.)	**Long-term actions** (pro-active approach, reduces vulnerability via planning supply, demand and impact measures)
Supply increase	- Use of marginal water sources - Relaxing environmental constraints - Improvement of efficiency	- New storage facilities and improved operation - Water transfers and use exchange - Non-conventional resources (wastewater, desalination)
Demand reduction	- Restriction on municipal uses - Restriction on annual crops - Water saving campaign - Mandatory rationing	- Dual municipal distribution networks - Water recycle in industries - Reduction of irrigation consumption (new crops and irrigation techniques)
Impact minimisation	- Temporary reallocation of resources - Public aid and tax relief - Rehabilitation programs	- Early warning system and drought contingency plan - Quality-based reallocation of water resources - Insurance and economic policies

Mitigation measures: reactive vs proactive

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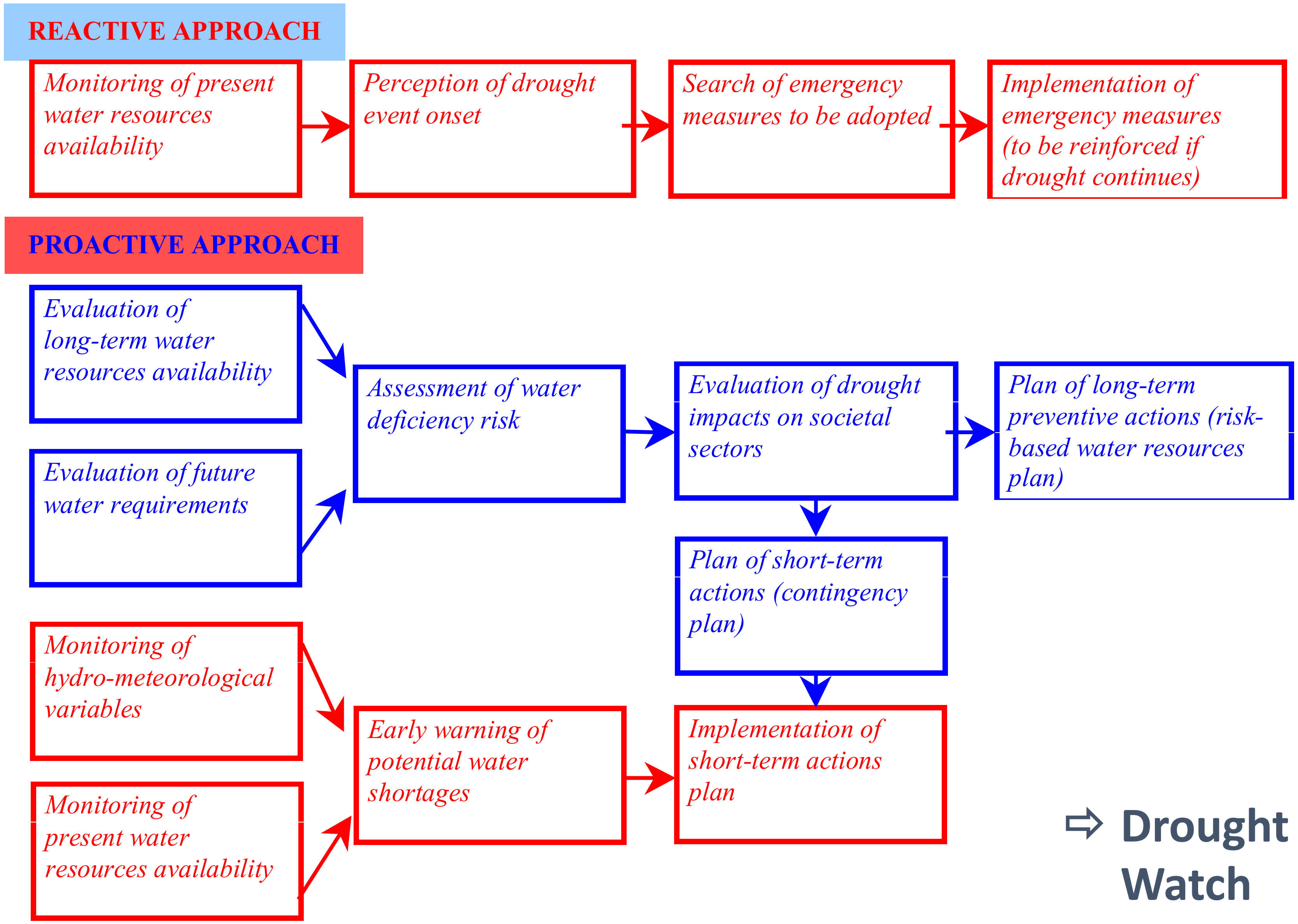

⇨ Drought Watch Systems

Mitigation measures: planning difficulties

- Inadequate understanding of natural drought phenomenon
- Lack of an early warning of water deficiency based on monitoring of hydrometeorological variables and water availability
- Difficulty in quantifying the impacts of drought on different sectors (economy, environment, society)
- Low appreciation of a pro-active approach for coping with natural hazards
- Strong conflicts among different groups of interest
- Legal and institutional constraints on the implementation of drought mitigation measures
- Inadequate development of tools aimed to assess the identified measures and to support the decision-making process;
- Lack of a consolidated (horizontal) coordination among water management agencies and of (vertical) communication among different decision levels.

↳ Many worldwide countries started to implement a drought monitoring and diagnostic system

blue: natural science/engineering; red: economical issues; brown: societal issues; black management issues