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Effects of evapotranspiration on the water balance of the Valley of Mexico

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RESUMEN

La Cuenca del Valle de México tiene una superficie de recarga de 9587 km^2. Los datos climáticos obtenidos en 82 estaciones se usaron para calcular los valores de precipitación anual de cada una de las subcuencas que la integran, obteniéndose que el promedio anual total de agua incidente en la cuenca es de 226 m^3/s (de 1980 a 1985).

La evaluación de varias ecuaciones empíricas y cuasi-empíricas para el cálculo de la evapotranspiración real derivaron en subestimaciones del 15 al 20% por el método de Turc, contrastando con valores demasiado altos obtenidos con las ecuaciones de Morton. Los métodos de Blassey-Morin, Coutagne y Budyko fueron considerados como los más cercanos al valor de la evapotranspiración real, la cual dio un promedio del 80 % de la precipitación total de un ciclo anual.

Las zonas montañosas con sustratos volcánicos, tales como la Sierra Chichinautzin, pierden entre el 50 y 60% del agua por evapotranspiración, mientras que sus partes bajas y las planicies del norte, localizadas entre la Sierra de Guadalupe y Pachuca, alcanzan un rango entre el 85 y 95 %. La mayor infiltración se espera que ocurra en las zonas altas de las cadenas montañosas, especialmente en los picos de la Sierra de Las Cruces, Sierra Chichinautzin y Sierra Nevada. Las fórmulas aplicadas incorporan varios factores climatológicos tales como precipitación total, temperatura, duración de la insolación, latitud y humedad relativa; pero la composición del subsuelo y sus parámetros geotécnicos no fueron considerados.

PALABRAS CLAVE: Evapotranspiración, precipitación, balance de agua, México D.F., Valle de México.

ABSTRACT

The total recharge area of the Valley of Mexico is 9587 km^2. Climatological data from 82 weather stations were used to calculate annual precipitation values for single subbasins. The total precipitation volume in the Valley of Mexico from 1980 to 1985 was 226 m^3/s.

Various empirical and semi-empirical equations resulted in underestimations of the actual evapotranspiration ET_{actual} by 15 to 20% for the Turc-method, whereas the equations of Morton yielded too high values. The methods of Blassey-Morin, Coutagne and Budyko are the most reliable ones, yielding an average percentage of 80% of the total yearly precipitation.

Volcanic mountain ranges, such as the Sierra Chichinautzin lose 50% to 65% by evapotranspiration, whereas their foothills and the northern plains between Sierra Guadalupe and Pachuca range between 85% and 95%. The largest infiltration is expected at mountain ranges, especially peak regions of the Sierra Las Cruces, Sierra Chichinautzin and Sierra Nevada. The formulas include various climatological factors such as the amount of rainfall, temperature, duration of insolation, latitude, or relative humidity but the composition of the subsoil and its geotechnical parameters were not considered.

KEY WORDS: Evapotranspiration, precipitation, water balance, Mexico City, Valley of Mexico.

INTRODUCTION

The large metropolis of Mexico City is confronted with a fast growing population rate and increasing water demand. Approximately 20 million people consume 62 m^3/s of water (1955 $Mm^3/year$). 42 m^3/s are pumped from aquifers in the valley, whereas 20 m^3/s come from rivers, wells and lakes outside the recharge area. Subterranean flow systems are radially directed from surrounding mountain regions towards the center of the valley. Extremely high pumping rates within the last few decades have severely impacted the aquifer system. Formerly artesian wells became downward directed flow systems (DDF, 1984), thus facilitating the infiltration of contaminants into the subsoil. Other effects, resulting from the overexploitation of the aquifer systems include the drawdown of groundwater levels, decreasing water quality and damage caused by subsidence of the ground.

The use of aquifer systems requires detailed knowledge of the total water circulation system and its balance. Rainfall represents the basic source of water input, but much water is lost by evapotranspiration, and some by runoff.

This paper provides calculations for the dimension of the recharge area and the total amount of precipitation for the total valley. As a first step, six empirical and semi-empirical methods for the calculation of the actual evapotranspiration are compared and evaluated for Mexico City.

1. GEOLOGY AND HYDROGEOLOGY

Based on topographical and geological maps, the catchment area of the Valley of Mexico was outlined, which resulted in an area of 9587 km^2.

Figure 1 shows a simplified geological map based on de Cserna *et al.* (1978), and also includes information of the hydrological subbasins within the Valley of Mexico. Due to its particular geomorphological basin position with enclosing mountain chains, no natural recharge is provided from areas outside the valley. Natural outflow for the inner

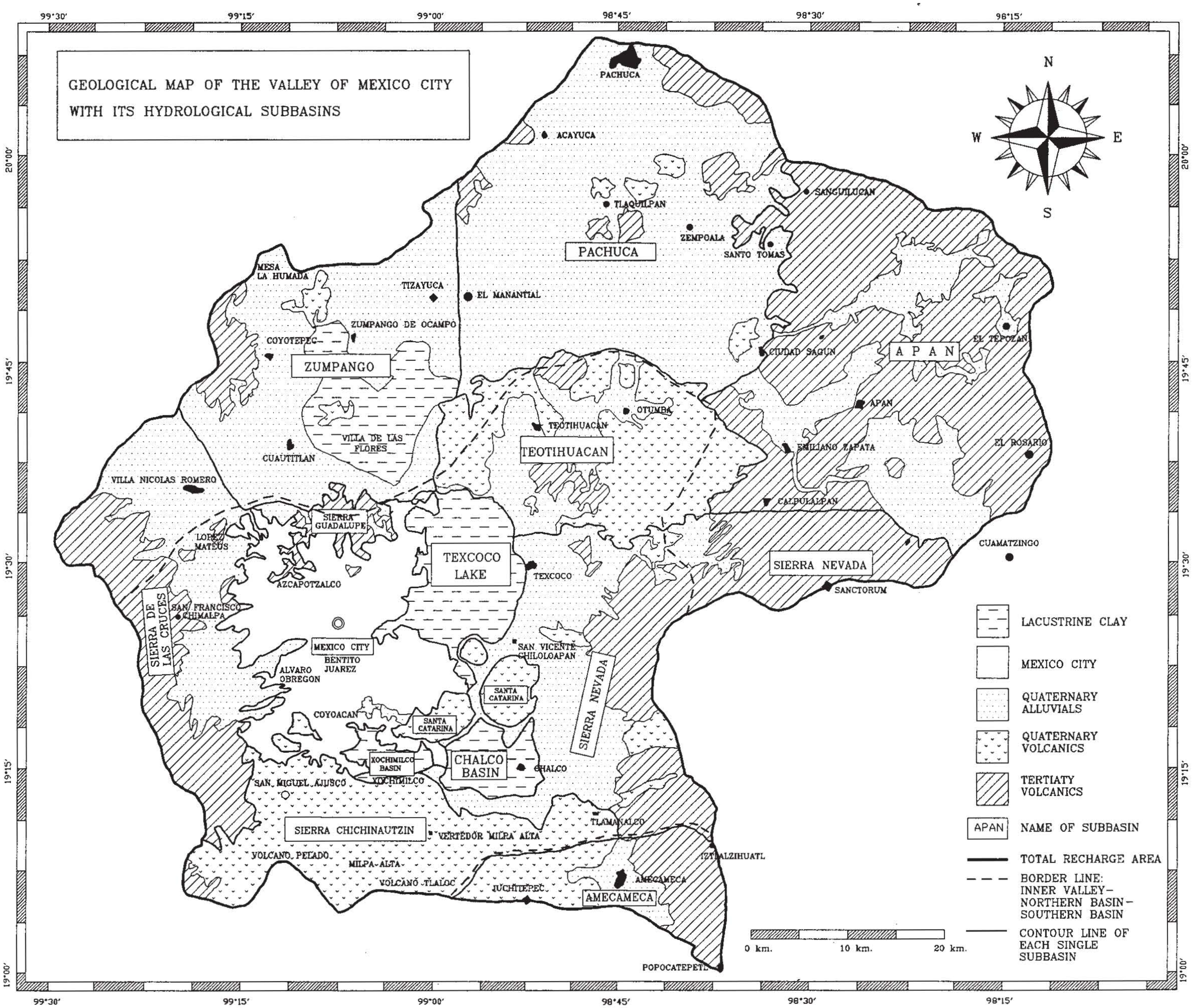

Fig. 1. Simplified geological map with hydrogeological information of the recharge area of the Valley of Mexico.

valley is absent; thus well extraction provides the only discharge.

Sierra Guadalupe, north of Mexico City, is a natural barrier between the inner valley of Mexico City and the northern subbasins. The northern subbasins represent partly a separate subbasin with an independent water flow system. Southward directed runoff in the area of Amecameca could indicate some underground flow out of the Valley.

The recharge area was divided into three main subbasins (Figure 1):

* The inner valley, which includes downtown Mexico City, the subbasins of Texcoco, Xochimilco and Chalco, and the mountain ranges of the Sierra Las Cruces, Sierra Chichinautzin, Santa Catarina, Sierra Nevada and Sierra Guadalupe (4110 km^2).
* The northern basin, which includes the area of Zumpango, Teotihuacan, Pachuca and Apan (5113 km^2).
* The southern basin of Amecameca, with an area of 364 km^2.

2. RAINFALL

The basins were divided into smaller sections based on variations of the geological underground and geotechnical properties, such as porosity and permeability (Figure 1). The Sierra Nevada can be divided into two sections, the mountain range of Tertiary volcanics, and the foothills with Quaternary alluvium. For each subbasin, an average precipitation value was extrapolated from isohyetal maps and from rainfall data. Average annual rainfall was obtained from SRH (1972) for the time period from 1920 to 1964, and from SARH (1982a) for 1950 to 1979. Annual editions from SARH (1980, 1981, 1982b, 1983, 1984, 1985) include precipitation data for 1980 through 1985.

Table 1 gives average annual precipitation values [mm or l/year] for some climatological stations, Table 2 for the mountains of the Sierra Chichinautzin and the foothills of the Sierra Nevada, and Table 3 and Table 4 show the average amount of rainfall [mm or l/year] and the total amount for each small area [in m^3/s]. Data from isohyetal maps contain an estimated rounding-off error of ± 10 mm.

Table 1

Calculation of the actual evapotranspiration [in mm/year] for selected climatological stations

Area	Subbasin of Pachuca	Subbasin of Pachuca	Subbasin of Zumpango	Subbasin of Zumpango	Subbasin of Apan	Sierra de Chichinautzin
Meteorological station	Santo Tomás	Pachuca	El Manantial	San Jerónimo Xonacahuacan	Cuamatzingo	Vertedor Milpa Alta
Average annual precipitation [mm]	900	500	500	900	800	660
Average annual temperature [°C]	16.2	13.0	15.3	12.5	13.5	15.3
Geological underground	Quaternary alluvial/Tertiary volcanics	Quaternary alluvial	Quaternary alluvial	Quaternary alluvial	Quaternary alluvial	Quaternary volcanics
Methods [in mm]:						
Empirical	450	200	200	360	320	265
Turc	360	428	450	569	565	544
Blassey-Morin	773	634	778	617	618	618
Morton	708	968	805	724	878	907
Budyko	780	484	485	793	709	617
Courtagne	696	-*	-*	585	615	671

* Precipitation value below 800mm ± 20%

Table 2

Basic input parameters for the area of the Sierra Chichinautzin mountains and the Sierra Nevada foothills

	Sierra Chichinautzin mountains	**Sierra Nevada foothills**
Geologic underground	Quaternary volcanics (Q_v)	Quaternary alluvials and tuffs (Q_{al})
Average annual precipitation	900 mm	700 mm
Average annual temperature	ca. 12.0°C	ca. 15.8°C
Dimension of the area	721.38 km^2	669.81 km^2
Albedo effect r	0.20	0.20
Insolation duration n (annual average)	6.8 h	6.7 h
Maximal insolation (latitude 20° N)	12.1 h	12.1 h
Relative humidity	63%	61%

Table 3

Calculation of ET_{actual} for the inner basin of the Valley of Mexico

Basin of Mexico City	Temp. [°C]	P [mm]	P_{total} [m³/s]	Area [km²]	ET_{real} [mm]	ET_{real} [m³/s]	ET_{real} [mm]	ET_{real} [m³/s]	ET_{real} [mm]	ET_{real} [m³/s]
Method					Empirical	Empirical	Turc	Turc	Coutagne	Coutagne
Area										
Mexico City (Center and Lake Texcoco)										
Lacustrine Clay (Ql)	15	600	22.08	1160.31	420	15.45	506	18.62	600 (660)	22.08 (24.28)
Sierra Chichinautzin										
a. Mountain range (Qv)	12	900	18.18	636.88	360	7.27	556	11.23	570	11.51
b. SW-Flank (TQv)	12.5	1450	0.66	14.38	725	0.33	636	0.29	585	0.27
Santa Catarina										
a. Quat. volcanics (Qv)	16	650	2.80	135.63	260	1.11	546	2.35	650 (690)	2.80 (2.97)
Sierra Guadalupe										
a. Mountain range (Tv, TQv)	16	650	1.27	61.56	390	0.76	546	1.07	650 (690)	1.27 (1.35)
b. Foothills	17	750	1.31	55	300	0.52	613	1.07	720	1.26
Sierra Nevada										
a. Mountain range (Tv, TQv)	12	950	10.89	361.56	570	6.54	566	6.49	570	6.54
b. Foothills (TQc, Qal)	15	700	10.86	489.06	280	4.34	555	8.61	660	10.24
Sierra Las Cruces										
a. Mountain range (Tv, TQv)	12	1200	10.57	277.81	600	5.29	603	5.31	570	5.02
b. Foothills (TQc)	14	950	8.47	281.25	380	3.39	619	5.52	630	5.62
Teotihuacan										
a. Mountain range (Qv)	15	600	6.55	344.38	300	3.28	306	3.34	600 (660)	6.55 (7.21)
b. Foothills (TQc, Qal)	15.5	600	4.54	238.44	240	1.81	512	3.87	600 (675)	4.54 (5.10)
c. Volcanics (Tv, TQv)	15	700	1.20	54.06	420	0.72	555	0.951	660	1.13
Total			**99.36**			**50.82**		**68.71**		**78.80 (82.48)**

3. ACTUAL EVAPOTRANSPIRATION (ET_{actual})

Birkle (1994) calculated the potential evapotranspiration (ET_{pot}) for several climatological stations, which is defined as the maximum possible evaporation under given meteorological conditions above a free water surface. For more realistic calculations of water balance, the effective or actual evapotranspiration (ET_{actual}) should be considered. It is defined as the actual amount of evaporation and transpiration of a surface, which results from a water-limited surface under certain meteorological conditions. For normal continental climate, such as in the Valley of Mexico, ET_{pot} exceeds ET_{actual}. When precipitation values exceed ET_{pot}, it can be assumed that ET_{pot} is equal to ET_{actual}.

ET_{actual} may be accurately measured with field instruments such as lysimeters, which are practically unavailable in the Valley of Mexico. Hence ET_{actual} will be calculated with empirical and semi-empirical equations as part of this study. The comparison of their results on local and regional scale will give information on the applicability for large recharge areas such as the Valley of Mexico.

3.1. Methods

Six empirical methods were used for the calculation of ET_{actual}. The symbols are listed in appendix 1.

Previous estimates

The following estimated and calculated values have been provided by previous authors:

50% of the precipitation is lost in the form of evapotranspiration in the Sierra Chichinautzin (CHCVM, 1967), Sierra Las Cruces (DGG, 1983; SRH, 1976) and in the Sierra Nevada (DGG, 1983; SRH, 1976). From modelling results, Ortega and Farvolden (1989) obtained infiltration rates of 50% ± 5% for the Sierra Chichinautzin, 25% ± 5% for the Sierra Las Cruces and 35% ± 5% for the Sierra Nevada.

Thus the following values for ET_{actual} were estimated (in percentage of precipitation) for different types of ground:

Lacustrine clay	70%	(1.1)
Quaternary alluvial	40%	
Quaternary volcanics	40%	
Tertiary volcanics	60%	

Turc (Gray, 1973)

$$ET_{actual} = \frac{P}{\left[0.9 + \left(\frac{P}{J}\right)^2\right]^{0.5}} \qquad (2.1)$$

where: $J = 300 + 25 \cdot T + 0.05 \cdot T^3$.

Table 4

Calculation of ET_{actual} for the subbasins of the Valley of Mexico

Subbasins	Temp. [°C]	P [mm]	Ptotal [m³/s]	Area [km²]	ET_{real} [mm]	ET_{real} [m³/s]	ET_{real} [mm]	ET_{real} [m³/s]	ET_{real} [mm]	ET_{real} [m³/s]
Method					Empirical	Empirical	Turc	Turc	Coutagne	Coutagne
Area										
N-part of the Sierra Las Cruces										
a. Foothills (Qal)	15.2	960	7.02	230.69	384	2.81	653	4.78	666	4.87
b. Mountain range (Tv)	13	1280	4.65	114.69	640	2.33	645	2.35	600	2.18
NE-part of the Sierra Nevada										
a. Mountain range (Tv)	13.5	800	7.98	314.5	480	4.79	565	5.63	615	6.13
b. Foothills (TQc, Qal)	14.7	650	1.02	52	260	0.43	527	0.87	650 (651)	1.02 (1.07)
N-part of Teotihuacan										
a. Mountain range (Qv)	14.2	650	2.90	140.69	325	1.45	520	2.32	636	2.84
b. Volcanics (Tv, TQv)	16.5	700	0.26	11.56	420	0.15	580	0.21	700 (705)	0.26 (0.26)
N-part of the Sierra Guadalupe										
a. Mountain range (Tv, TQv)	15.5	650	0.32	15.56	390	0.19	539	0.27	650 (675)	0.32 (0.33)
Subbasin of Apan										
a. Quat. alluvial (Qal)	13.3	780	11.28	456.13	312	4.51	554	8.01	609	8.81
b. Tert. volcanics (Tv)	15	760	28.46	1180.75	456	17.07	581	21.75	660	24.71
Subbasin of Pachuca										
a. Quat. alluvial (Qal)	14.2	630	27.84	1393.75	252	11.14	510	22.54	630 (636)	27.84(28.11)
b. Quat. volcanics (Qv)	14.2	650	0.81	39.38	325	0.41	520	0.65	636	0.79
c. Tertiary volcanics (Tv, tuffs)	14.2	670	3.02	142.19	402	1.81	529	2.39	636	2.87
Subbasin of Zumpango										
a. Lacustrine clay (Ql)	16	650	4.69	227.56	455	3.28	546	3.94	650 (690)	4.69 (4.98)
b. Quat. alluvial (Qal)	15.8	650	14.26	691.69	260	5.70	543	11.91	650 (684)	14.26(15.00)
c. Quat. volcanics (Qv)	15.8	630	0.58	29.19	315	0.29	533	0.49	630 (684)	0.58 (0.63)
d. Tertiary volcanics (Tv, tuffs)	15.7	730	1.69	72.94	438	1.01	581	1.34	681	1.58
Subbasin of Amecameca										
a. Quat. volcanics (Qv)	14.5	850	3.47	128.75	372	0.83	603	2.46	645	2.63
b. Foothills (Qal)	13.9	930	2.07	70.13	340	1.39	611	1.36	627	1.39
c. Mountains (Tv)	12.5	970	5.08	165.13	485	2.54	583	3.05	585	3.06
Total (Subbasins)			**127.45**			**62.14**		**96.32**		**110.84 (112.26)**
Total: Valley + Subbasins			**226.82**			**112.95**		**165.04**		**189.64 (194.74)**

Based on 254 basins distributed all over the world, Gray (1973) obtained this equation considering the annual average temperature T [in °C] and the annual rate of precipitation P [in mm].

Blaney-Morin (Blaney, 1959; Criddle, 1958).

$$u = K \sum_{1}^{m} p_1 T\,(114-h)/100\ . \qquad (3.1)$$

The daytime hourly percentages of the year p_l may be computed from the Sunshine tables (U.S. Weather Bur. Bull., 1905). T represents the mean monthly temperature (in °F) and h the annual mean relative humidity (in per cent). The annual, seasonal or monthly consumptive use coefficient K for irrigated crops can be found in tables by Blaney (1959) and Criddle (1958).

F.I.Morton (1965)

$$ET_{actual} = (1-r)\,R/ - ET_{pot} \qquad (4.1)$$

where

$R/ = R_i \cdot$ number of days per month / H_v

$R_i = R_A\,(a + b \cdot n/N)$

$H_v = 597.3 - 0.564T$

$ET_{pot} = 25.4 \cdot 10^{-4} \cdot R_i\,(4.806T + 33.98)$.

Morton (1965) proposed this relation based on the incident shortwave radiation $R/$ and the potential evapotranspiration ET_{pot}. The value for the albedo r depends on the type of vegetation. Values of 0.12 to 0.24 for corn fields in North America, 0.10 to 0.25 for cereal and wheat in Western Europe, and 0.10 to 0.12 for pine forest in Western

Europe are given by Dunne and Leopold (1978). In general, a value of 0.15 to 0.20 can be used for most areas.

The solar radiation R_A in $MJ\ m^{-2}\ day^{-1}$ is dependent on latitude and day of year. Jáuregui (1977) proposed a value of 0.270 for the constant *a* and a value of 0.550 for the constant *b* in the area of the Universidad Nacional Autónoma de México (UNAM), south of Mexico City. The average daily duration of insolation *n* and the average annual temperature *T* [°C] are taken from climatological stations. The maximum possible duration of insolation *N* depends on the latitude and the time of year. The values for solar incident radiation above a free water surface R_i [MJ m-2 day-1], the monthly incident radiation $R/$ [mm], and the latent vaporization heat H_v [cal/cm3 or cal/gr] can be calculated from the data above.

Budyko (Kuzmin & Vershinin, 1974)

$$ET_{actual} = \sqrt{\frac{R_n \cdot P}{H_v}\left[1-\exp(-R_n / H_v \cdot P)\right]\tanh(H_v \cdot P / R_n)} \qquad (5.1)$$

where

$$R_n = R_i\ (1\text{-}r) - R1 \qquad (5.2)$$

$$R_n = 0.62 \cdot R_i - 24 \qquad (5.3)$$

$$R1 = \sigma T^4\ (0.56 - 0.0924\ \sqrt{e_2})\ (0.10 + 0.90\ n/N) \qquad (5.4)$$

The equation of Budyko is very similar to the equation of Morton. The solar incident radiation above a free water surface R_i [MJ m-2 day-1 or langleys/day] and the latent vaporization heat H_v can be calculated as shown in (4.1). For the calculation of the net longwave radiation $R1$ [MJ m-2 day-1], the vapour pressure of the air e_2 [mm Hg] at a height of 2 m must be known (5.4). Finally, the equations (5.3) (Dunne and Leopold, 1978) and (5.2) estimate the net radiation R_n [MJ m-2 day-1].

M. Coutagne (Remenieras, 1974)

$$ET_{actual} = 210 + 30T \qquad (6.1)$$

requirements: $P = 800$ mm ± 20%
Latitude = 30° - 60°N

Equation (6.1) of M. Coutagne depends on the amount of precipitation *P*, the latitude of the location and its annual average temperature *T* [°C]. Coutagne showed that (6.1) is only valid for areas with the requirements listed.

3.2. Restrictions

The equation of Turc does not consider important parameters such as insolation. The availability of average precipitation and temperature values for each subbasin allows its application for the entire recharge area. The method of Blaney-Morin is applicable only in farming areas such as the foothills and plains in the Valley of Mexico. The consumptive-use coefficient *k* represents a correction factor for various types of irrigated crops. The equations of Morton and Budyko include more parameters than other methods, including insolation, solar radiation, latent vaporization heat, potential evapotranspiration (Morton), precipitation (Budyko) and temperature. These data requirements restrict application for some single climatological stations. The method after M. Coutagne is based on field testing in the United States. It is basically valid for regions with a range in latitude of 30° to 60°N and a precipitation value of 800 mm ± 20%. Mexico City is located at a latitude of 20°N; thus the equation could result in small errors.

3.3. Evapotranspiration at local meteorological stations

Few stations have enough climatological data for using the equations. Six stations, for which a large collection of climatological data was available, were selected to compare the validity and applicability of the evapotranspiration equations and the possible deviations between them (Table 1). The calibration of the different methods will be used to evaluate the total result for the entire basin of Mexico City (see 3.5.).

The calculations were performed for the time period of 1980 to 1985 using climatological data (rainfall, temperature, insolation, wind velocity and relative humidity) from the annual data (SARH, 1980, 1981, 1982b, 1983, 1984, 1985) for each station.

Previous estimates, based on data by CHCVM (1967), DGG (1983), SRH (1976) and Ortega and Farvolden (1989), produced very low ET_{actual} values. The equation after Turc is 10 to 50% below the average values of the other equations. Blaney-Morin and Coutagne provide a stable range of intermediate values, whereas the Budyko method shows some fluctuations in both directions. Values for ET_{actual} obtained by the Morton method exceed the total rainfall at several sites, suggesting the absence of infiltration. It can be assumed that the Morton method, which does not consider the amount of rainfall, slightly overestimated the values for those areas. The method after Coutagne should not be applied for sites with less than 800 mm ± 20% for *P*, such as Pachuca or El Manantial.

3.4. Evapotranspiration of selected sub-basins

The mountain range of the Sierra Chichinautzin was chosen as representative of areas with volcanic underground and cooler atmospheric conditions, whereas the foothill area of the Sierra Nevada represents regions with sedimentary deposits and higher atmospheric temperatures. For both areas, several climatological stations with an extended data base were available. The eastern part of the Amecameca basin (Quaternary volcanics) was included in the Sierra Chichinautzin region, and its western part in the Sierra Nevada region (Quaternary alluvials and Tertiary volcanics).

The calculations were performed for 1980 to 1985. For this time period, an average temperature and precipitation value was derived for each area, using isohyetal maps and climatological data from SARH (1980, 1981, 1982b, 1983, 1984, 1985). Table 2 shows the basic input parameters for the equations. Figure 2 and Figure 3 show the computed results for each method.

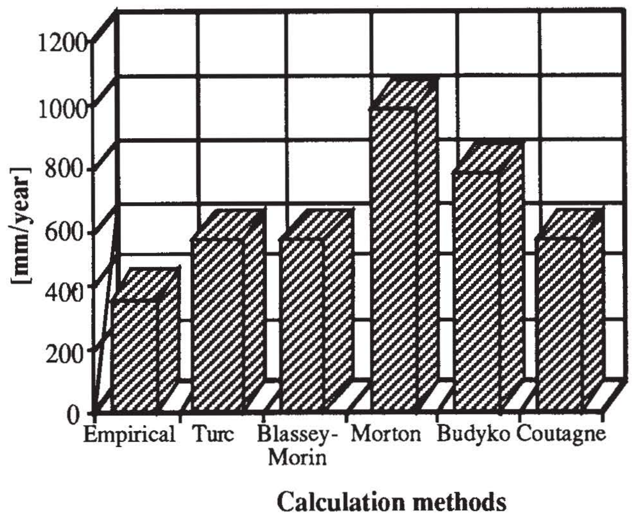

Fig. 2. Calculation of the actual evapotranspiration for the mountains of the Sierra Chichinautzin using various empirical equations.

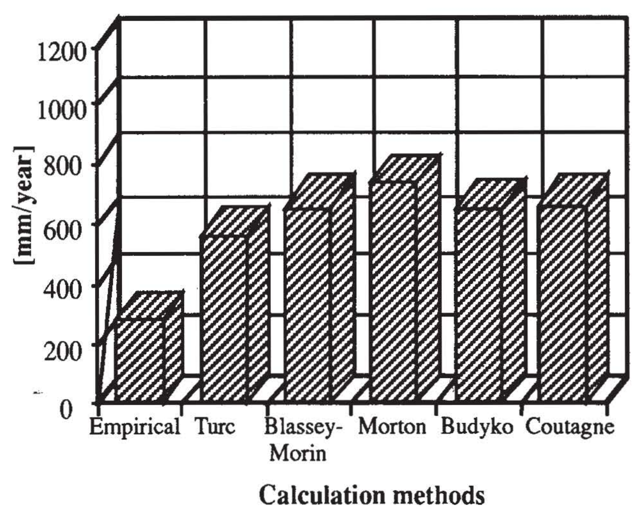

Fig. 3. Calculation of the actual evapotranspiration for the foothills of the Sierra Nevada applying various empirical equations.

The values of ET_{actual} in the Sierra Chichinautzin are scattered over a wide range of 360 to 985 mm for several equations (Figure 2). Turc, Blaney-Morin and Coutagne provide similar values of 560mm. As for Morton and Budyko (985 and 779mm respectively), 560mm for ET_{actual} seems to be 10 to 20% too low. An annual average amount of 620 to 680 mm for ET_{actual} in the mountains of the Sierra Chichinautzin might be a realistic empirical estimation.

The methods of Blaney-Morin, Budyko and Coutagne provided a consistent value of 604 to 660 mm for ET_{actual} for the foothills of the Sierra Nevada (Figure 3). Previous estimates yield a very low value of 280 mm, and the Turc result is 15 % lower than the former equations (555 mm). The results from the Morton equation fluctuate significantly for different climatological conditions, being 10% to 20% above the average of other methods. The agreement between Blaney-Morin, Budyko and Coutagne suggests a value of 650 mm for ET_{actual} for the foothills of the Sierra Nevada from 1980 to 1985.

Although the Sierra Nevada has higher annual and monthly temperatures than the Sierra Chichinautzin, its value for ET_{actual} from the Budyko equation is slightly lower. This apparent contradiction may be due to the influence of P and n for the Budyko method, whereas variations in temperature can be neglected. In comparison, results obtained by Blaney-Morin are affected by differences in temperature.

3.5. ET_{actual} for the entire valley

For the calculation of the entire valley, average values for precipitation, temperature and relative humidity were calculated and assigned to each subbasin (Figure 1). The lack of climatological data restricted the application to three methods (Previous estimates, Turc and Coutagne). The more detailed equations of Budyko, Blaney-Morin and Morton required a large data set. The results for the inner basin and the northern and southern subbasins of Mexico are shown in Table 3 and 4. The values in parentheses represent the original results of the equations, which were corrected when ET_{actual} appeared to be larger than the rainfall.

The following abbreviations were used:

Q_l	Quaternary lacustrine clays
Q_{al}	Quaternary alluvials
Q_v	Quaternary volcanics
TQ_v	Tertiary-Quaternary volcanics
TQ_c	Tertiary-Quaternary pyroclastics
T_v	Tertiary volcanics

The previous estimates and Turc method led to values of 113 m³/s and 165 m³/s, respectively, for ET_{actual} of the Valley of Mexico. As shown above, both methods underestimate the effect of evapotranspiration. The agreement of the results of the Coutagne-, Budyko-, Blaney-Morin- and Morton methods (3.3. and 3.4.), led us to assume the validity of the Coutagne equation, with 190 m³/s for ET_{actual} from 1980 to 1985 for the entire basin of Mexico.

3.6. Distribution of ET_{actual} in the main recharge area

The Coutagne method (Table 3 and 4) was used to compare the main recharge areas of the basin: The mountain ranges of the Sierra Chichinautzin, Sierra Nevada and Sierra Las Cruces. Figure 4 illustrates the amount of rainfall and calculated values for ET_{actual} within the mountain ranges, excluding the foothills. Assuming the incorporation of the northern and southern subbasins in the total water system, areas such as the Quaternary volcanics in the western part of Amecameca were attached to the mountain range of the Sierra Chichinautzin.

The large area of 841 km² causes the largest volume of precipitation for the Sierra Nevada, but low permeability of Tertiary basalts and andesites prevents extensive infiltration. Approximately 65% of the rainfall is lost by evapotranspiration, whereas the percentages for Chichinautzin and Las Cruces are 59% and 47%, respectively. Las Cruces has the highest average precipitation of the entire valley (1280 mm in the northern part, 1200 mm in the central part), but its small area (392 km²) restricts the total amount of rainfall to 15. 2 m³/s.

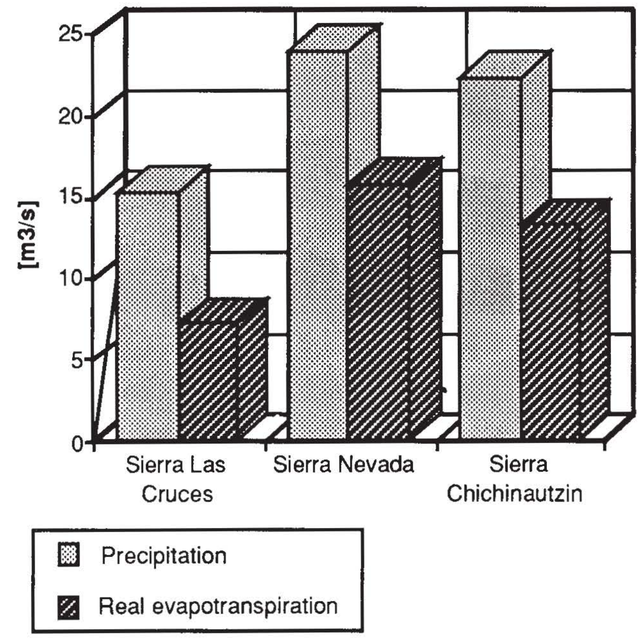

Fig. 4: Calculated values for the annual precipitation and evapotranspiration (after Coutagne) for the mountain ranges surrounding Mexico City.

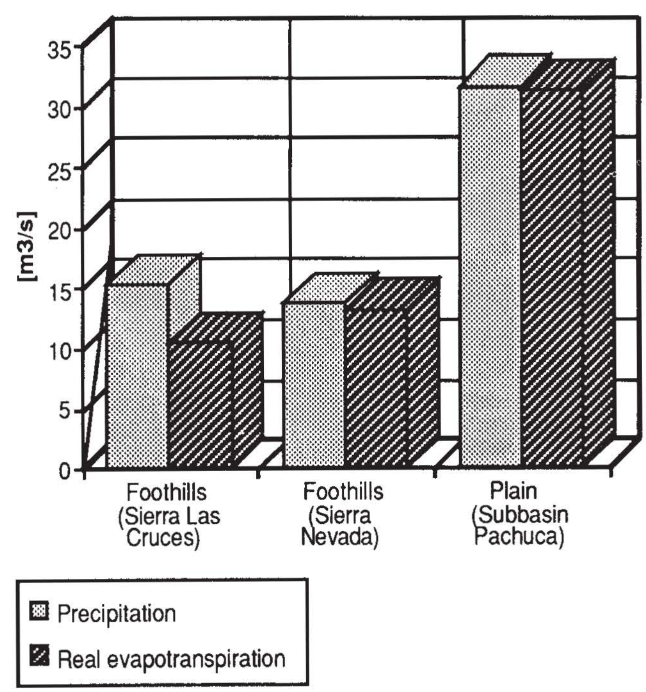

Fig. 5: Calculated values for the annual precipitation and evapotranspiration (after Coutagne) of selected foothills and plain areas within the Valley of Mexico.

The values of P and ET_{actual} for the foothills calculated with the Coutagne method are illustrated in Figure 5. The subbasin of Pachuca was selected as a typical example for a flat area with alluvial ground. The large size of the northern plain causes large absolute values of rainfall but low air humidity, high temperatures and low precipitation (650 mm) reduce the infiltration. The situation is similar for the foothills of the Sierra Nevada, where approximately 95% of rainfall is lost by evapotranspiration, whereas higher precipitation (ca. 950 mm) at the foothills of Las Cruces allow higher infiltration and runoff (ca. 30%).

INTERPRETATION

The previous estimates, Turc and Coutagne methods resulted in a wide range of values between 112 m³/s and 189 m³/s for the total recharge area. The evaluation of the applicability of the equations (3.3. and 3.4.) indicated that the previous estimates produced values much too low for ET_{actual}. The Turc method was approximately 20% to 30% below the average for more comprehensive methods such as Budyko, Morton and Blaney-Morin. Values derived from the Coutagne equation, fall within the range of these methods. In areas with little rainfall, such as in most of the northern subbasins, the Coutagne method yields the total loss of the precipitation water by evapotranspiration. However, humid climatic conditions in those areas and high permeability values of the alluvial subsoil indicate that some infiltration occurs at least during heavy rainfall periods.

The comparison of these methods suggests that the actual value for ET_{actual} of the entire valley should be 20% above the value derived from the Turc method, which corresponds to results from the Coutagne equation.

180 to 190 m³/s for ET_{actual} of the entire valley appears to be realistic value, which would comprise approximately 80%±5% of the total precipitation. Lower average percentages of 62% for Germany (Liebscher, 1982) and 70% for the United States (Sharma, 1985) can be explained by the higher latitude and lower mean temperatures. Arid regions in the western U.S. indicate values for ET_{actual} with over 90% of total precipitation (Sharma, 1985).

Urban influences seem to have minor effects on the water balance of the entire valley because:

The area of the city covers less than 15% of the total catchment area. The pavement of the inner city has similar low permeability as the clayey ground; low precipitation rates (600 mm/year) of the inner city are of little importance in terms of the total water input.

CONCLUSIONS

We estimate an absolute value of 226 m³/s for the precipitation and 180 to 190 m³/s for the actual evapotranspiration for the Valley of Mexico. The most reliable methods for the calculation of ET_{real} are represented by the equations of Budyko, Blaney-Morin and Coutagne, whereas calculations with data from previous authors and with the Turc equation give too low values for ET_{actual}. The Morton method appears to overestimate the effect of evapotranspiration by 10 to 20%, especially in areas with little rainfall.

As an average for the entire valley, approximately 80% of the rainfall is lost by evaporation and transpiration. The major part of the remaining water is assumed to infiltrate into aquifers, whereas a smaller part is lost by drainage or in evaporation lakes. Evapotranspiration dominates in the foothills and plains of the valley, where approximately 85% to 95% of the rainfall is unavailable for infiltration. The mountain ranges of the Sierra Chichinautzin, Sierra Las Cruces and Sierra Nevada with precipitation rates between 900 and 1200 mm/year lose 50% to 65% of their annual rainfall by evapotranspiration processes, and represent the main recharge areas of the valley.

The equations consider a variety of climatological parameters such as annual temperature, duration of insolation and precipitation rate, but neglect geological characteristics such as the type of rock and hydrogeological properties. Field experiments, including the installation of lysimeters, may result in more realistic values for the infiltration rate, and would provide information on the amount of precipitation which is lost by runoff and evapotranspiration.

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APPENDIX 1

Symbols

a, b	empirical constants
ET_{pot}	potential evapotranspiration [mm/month]
ET_{act}	actual evapotranspiration [mm/month]
h	annual mean relative humidity in percent
H_v	latent vaporization heat [cal/gr]
K	consumptive use coefficient (0.75-0.85 for corn)
n	time period of insolation [hours/day]
N	theoretical maximal time period of insolation [hours/time]
p	latitude coefficient
p_l	daytime hours percentages of the year
P	precipitation [mm]
P_k	corrected precipitation value (with factor 1.1)
r	albedo [dec.]
R_A	solar extraterrestrial radiation [MJ m^{-2} day^{-1}]
R_i	solar incidental radiation above a free water surface [MJ m^{-2} day^{-1}]
R_n	net radiation [MJ m^{-2} day^{-1}]
$R/$	monthly incidental radiation [MJ m^{-2} day^{-1}]
R_l	net radiation of large waves interchanging beween the atmosphere and the water volume [MJ m^{-2} day^{-1}]
σ	Stefan-Boltzmann constant [$1.171 \cdot 10^{-7}$ cal/cm²/°K/day]
T	mean monthly or annual temperature (in °F or °C)

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