PROCEEDINGS, 13th Indonesia International GEOTHERMAL Convention & Exhibition 2013
Assembly Hall - Jakarta Convention Center Indonesia, June 12 – 14, 2013

# STUDY OF GROUNDWATER AVAILABILITY AS NATURAL RECHARGE FOR HYDROTHERMAL RESERVOIR IN SEMI-ARID REGION

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## ABSTRACT

According to Koppen, the climate in Indonesia is divided into tropical, arid/semi-arid, mild temperate, continental and polar climate. Tropical climate covers Sumatra, Jawa, Kalimantan, and Papua. Arid/semi arid climate extends over East Nusa Tenggara region and its vicinity. Mild temperate climate covers almost the entire Indonesian archipelago, especially Sumatra, Kalimantan, and Papua, while polar climate covers Jaya Wijaya Mountains.

Most of the geothermal fields in Indonesia are hydrothermal system and have similar tropical climate. Tropical climate area like Jawa preserves precipitation values of at least 60 mm/month, while in arid/semi-arid climate area like East Nusa Tenggara has an average rainfall of 20-40 mm/month. Groundwater potential from unconfined aquifer in Jawa was recorded 38.8 billion $m^3$/year meanwhile calculation from confined aquifer resulted 10.1 billion $m^3$/year. Groundwater potential from unconfined aquifer in East Nusa Tenggara was recorded 2 billion $m^3$/year whereas confined aquifer supplied 0.3 billion $m^3$/year. From those data, annual groundwater in arid/semi-arid area is less than tropical climate area, and it tends to remain in a deficit. These conditions will affect the supply of groundwater to the geothermal reservoir.

One of the main strategies to sustain reservoir is by estimating the availability of groundwater supply based on the calculation of limited precipitation and evapotranspiration value in water-balance method from Mock. This study can be used as the starting point in order to support the recommendations to maintain the reservoir on a long term economical periods.

## INTRODUCTION

Surface water can be a significant source of recharge water depending on the climatic situation. Under humid conditions, perennial rivers are prevalent while under arid or semi-arid conditions, short-lived rivers predominant. River, stream, lake, wetland, or ocean join together as surface water, precipitate and percolate to subsurface through geologic formation, yield reasonable amounts of groundwater called aquifer.

Artika (2012) calculated groundwater storage from surface water for utilizing artificial recharge areas in Kamojang, West Java. West Java is associated to tropical climate region with Sumatra, Jawa, Kalimantan, and Papua. Water balance in tropical climate region preserves average precipitation values of at least 60 mm/month, while in arid/semi-arid climate area like East Nusa Tenggara has an average rainfall of 20-40 mm/month. Annual groundwater in arid/semi-arid area is less than in tropical climate area, and it tends to remain in a deficit. These conditions will affect the supply of groundwater to the geothermal reservoir.

The purpose of this paper is to prove the insufficiency of groundwater storage in semi-arid regions and to draw a starting point in order to support the recommendations to maintain hydrothermal reservoir on a long term economical periods in semi-arid regions.

## CLIMATE CLASSIFICATION

The Koppen Climate Classification System is the most widely used system for classifying the world's climates. Its categories are based on the annual and monthly averages of temperature and precipitation (Peel, 2007).

According to Koppen Climate Classification System, Indonesia is grouped into Tropical Moist Climates that extend northward and southward from the equator to about 15 to 25 degrees of latitude. In these climates, all months have average temperatures greater than 18 degrees Celsius with annual precipitation is greater than 1500 mm (Lohmann, 1993).

Tropical climate covers Sumatra, Jawa, Kalimantan, and Papua. Arid/semi arid climate extends over East Nusa Tenggara region and its vicinity. Mild temperate climate covers almost the entire Indonesian archipelago, especially Sumatra, Kalimantan, and Papua, while polar climate covers Jaya Wijaya Mountains (Peel, 2007).

Koppen (1923) op. cit. Lohmann (1993) subdivided Tropical Moist Climates into 3 groups based on their seasonal distribution of rainfall. **Af** or tropical wet is a tropical moist climate where precipitation occurs all year long, with monthly temperature disparities are less than 3 degrees Celsius. **Aw** is a tropical monsoon climate, where yearly rainfall is equal to or greater than Af, but falls in the 7 to 9 hottest months. A slight rainfall occurs during the dry season. **Bs** is semi-arid or savanna has an extended dry season and has precipitation less than 1000 millimeters/year (Figure 1).


*Figure 1: Distribution of Koppen Tropical Moist Climates in Indonesia (www.reliefweb.int).*

## ATADEI HYDROTHERMAL SYSTEM

Atadei geothermal field is situated in the most eastern part of 7 potential geothermal areas in East Nusa Tenggara (Figure 2). The Atadei geothermal field located in Atadei Subdistrict, District of Lembata, about 45 km southeast of Lewoleba, capital city of Lembata District. Atadei has climate of Bs type and adjacent to Alor Strait and Sawu ocean.

Three prospect areas were determined by Nanlohy et al (2008) as shown in Table 1 and Figure 3 with possible geothermal potential about 40 MW.

*Table 1: Geothermal potential prospect areas in Atadei (ECFA, 2008).*

| No | Prospect | Areas | Geothermal Potential |
|---|---|---|---|
| 1 | Watuwawer | 4.5 $km^2$ | 20-30 MWe |
| 2 | Lewo Kebingin | 0.25 $km^2$ | 1-2 MW |
| 3 | Waru | 1.5 $km^2$ | 7-10 MW |

*Figure 2: Map of Potential Geothermal in Indonesia (ECFA, 2008).*

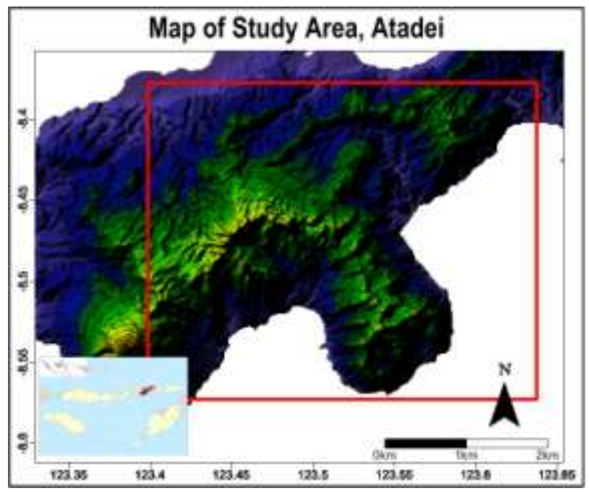


*Figure 3: Map of study area.*

### Geology

Lomblen Island is a part of the Banda Island arc system which comprises Upper Cenozoic volcanic rocks with volcanogenic and carbonates sediments. The volcanic rocks are dominantly of mafic to intermediate calc-alkaline composition and are uncomfortably underlain by the Tertiary rocks. The oldest rocks are of Miocene age and exposed on northern part of the island. The youngest rocks in the area in relation with the most recent volcanic event in the island occur on Mt. Ili Werung and Mt. Hobal, 6 km South East of the surveyed area (ECFA, 2008).

The Quaternary volcanic rocks consist of lava and pyroclastic deposits, which were mostly erupted from the vents of Mt. Watulolo, Mt. Atalojo, Mt. Benolo and Mt. Watukaba. These rocks are dominantly of basaltic andesite composition. However, there are deictic rocks exposed on a narrow area at the north Watukaba caldera wall. The secondary deposits are alluvial and debris avalanches deposits. The later is a very recent deposit due to slope instability of intensively altered volcanic rocks and buried the former sub district capital town of Atadei in 1979.

Atadei geothermal field is composed of Quaternary old and young volcanic rock unit. Its geological structures are characterized by Watuwawer and Bauraja calderas, NE-SW trend of Watuwawer and Mauraja normal faults, and NW-SE Waibana normal fault. Figure 4 shows that NW-SE and NE-SW are one probably controls the volcanism and the volcanic vents (ECFA, 2008).

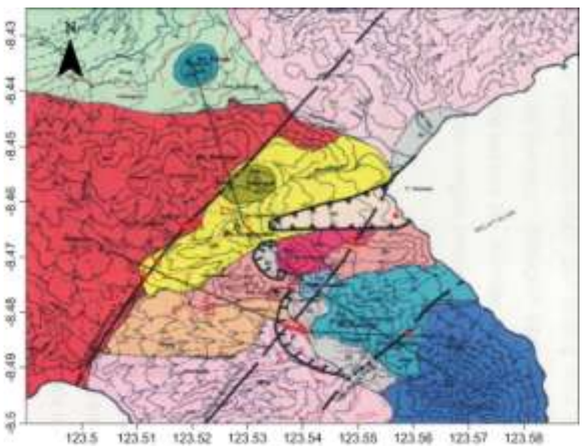

*Figure 4: Geology map of prospect areas (Nanlohy et al (2008).*

**Geochemistry**

Most thermal features in the Atadei geothermal area occur over area boundaries by a couple of NE-SW trending faults: Kowan and Lewo geroma faults in the North and South, respectively. Features include hot spring, steaming/hot grounds, and altered rocks.

Hydrothermal system is characterized by the appearance of springs as surface manifestations. Surface manifestations of Atadei hydrothermal system consist of hot springs (32-45°C) which mostly characterized by nearly neutral pH and bicarbonate type. In some areas, springs have high sulphate content, very low chloride content and low pH. No chloride waters discharge at the surface. Fumaroles (80-96°C), steaming ground (96-98°C) and altered rocks found in Watukaba caldera, on the western flank of Mt. Ilikoti and eastern flank of Mt. Benolo (ECFA, 2008).

The volcano-stratigraphy study and thermal manifestation suggest that the heat source of the Atadei geothermal area is beneath the Atalojo crater and Watukaba caldera. The intensive alteration mostly occurs in area boundaries the couple of NE Kowan and SW Lewogeroma normal faults. However, some samples taken from the western flank at Mt. Ilikoti show that the rocks have been extensively altered by neutral pH fluid (ECFA, 2008).

## GEOTHERMAL RESOURCE ASSESMENT

**Mass Flow Rate**

Electricity will be generated by modular scenario of 1 x 5 MW single flash separation by using the following equation:

$$vol = \frac{mass}{\phi \times S_L \times \rho_L}$$

The required steam flow mass is 2.44 kg/s (or 8.94 kg/s in water phase) with initial temperature of the reservoir 220°C (Nanlohy, 2010), cut-off temperature 180°C, porosity 10%, turbine inlet pressure 6 bara, condenser pressure 0.1 bara, turbine efficiency 80%, water saturation 40% and 60% steam saturation.

With mass flow rate of 2.44 kg/s, annual volume of groundwater (at a temperature of 30 °C) that possible needed to supply the reservoir is 7,086,136,900.76 L/year.

**Recharge Area**

Due to limited study in stable isotope $^{2}H$ and $^{18}O$ to trace the history and origin of groundwater, recharge area of Atadei is determined from assumptions based on morphology and geology conditions (Rahayu, 2012) as shown in Figure 5:

a. Recharge area is bounded by steep slopes.
b. Recharge area is bounded by the river (if there is a river system that flowed nearby).
c. Recharge area is adjusted to discharge spring rate, the significant the rate, the extensive the area.
d. Springs in the same geological condition are possibly having the same recharge zone.
e. Faults and geology structures are presumed as secondary porosity (ability to hold amount of water in reservoir) and high permeability zone that provides openings for fluids to pass through earth materials.

## WATER BALANCE CALCULATION

**Data**

Due to the fact that the availability of climatological data is very restricted in Atadei, water balance calculation using data from the nearest climatological station located in Maumere.

The climatological data ranged from 1973 to 1990, including precipitation data, solar radiation, wind speed, temperature, relative humidity, and evaporation (See Table 2 to Table 4).

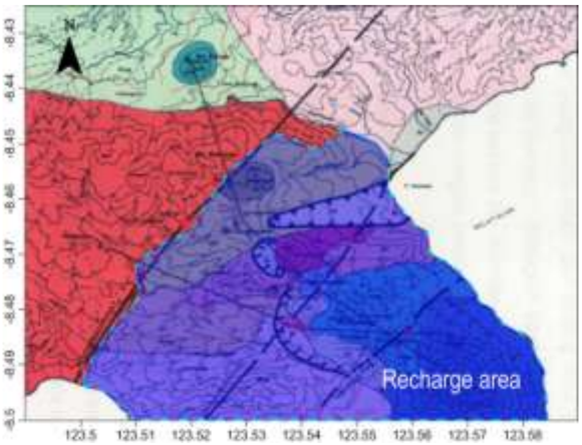


*Figure 5: Recharge area of Atadei by assumptions from Rahayu (2012).*

## Methodology

The Earth's hydrologic cycle consists of many varied and interacting processes involving all three phases of water. A schematic diagram of water flow from the atmosphere to the surface and subsurface, and in the long run back to the atmosphere is shown in Figure 6.

The hydrological cycle can be quantified in its simplest form using mass balance expression:

$P = E + TRO + \Delta S$

where

P is precipitation or rainfall (mm/time),

E is evapotranspiration,

TRO is total runoff, water that flows from a surface, e.g. a catchment ($m^3/s$ or liter/s)

ΔS is change (Δ) in groundwater storage (S), ΔS can be either positive or negative, as the storage increases or decreases.

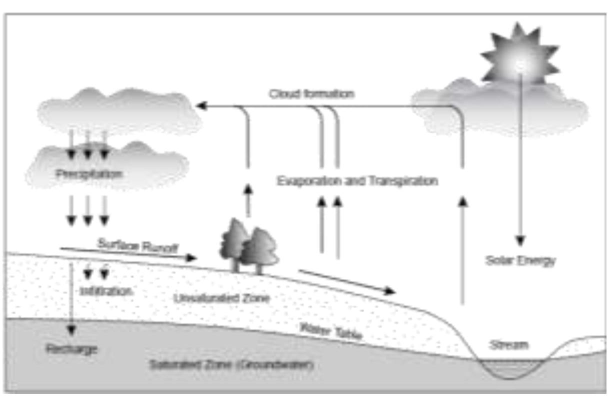


*Figure 6: Hydrological cycle.*

A method for predicting discharge rate based on mass balance was introduced by F. J. Mock in 1973 (Rahayu, 2010). Mock's water balance calculation is illustrated by Artika (2012) in Figure 7.

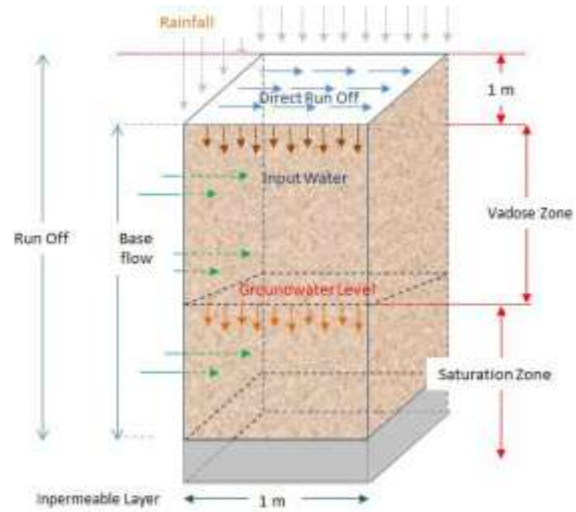


*Figure 7: Illustration of hydrodynamic models of water (Artika, 2012).*

***Evapotranspiration***

1. Potential Evapotranspiration

Potential evapotranspiration is the evapotranspiration that may occur in conditions of excessive water available. Sufficient availability of water is the most important factor of potential evapotranspiration.

Mock method adapted the empirical formula of Penman which used some climatological data of temperature, solar radiation, humidity, and wind speed. Penman potential evaporation calculation based on the circumstances that enable the necessary evaporation heat. The value of potential evapotranspiration in this study is 134-239 mm/day. Penman potential evapotranspiration formulated as follows:

$$E = \frac{AH + 0.27D}{A + 0.27}$$

where

- H (energy budget) = R (1-r) (0.18 + 0.55 S) - B (0.56 to 0.092 de) (0.10 + 0.9 S)
- D (the heat required for Evapotranspiration) = 0.35 (ea - ed) (0.01 k + w)
- A = slope of vapor pressure curve at the average temperature, (mmHg/°F)
- B = black body radiation at the average temperature, (mm $H_2O$/day)
- ea = saturated water vapor pressure (saturated vapor pressure) on temperature average (mmHg).
- R = solar radiation (mm/day)
- r = coefficient of reflection
- S = the average monthly percentage of solar radiation (%)
- ed = actual vapor pressure (actual vapor pressure), (mmHg = ea x h)
- h = relative humidity monthly averages (%).

k = coefficient of roughness of surface evaporation. k = 0.50 for surface water and k = 1.0 for surface vegetation value

w = wind speed monthly averages, (mile/day)

The amount of solar radiation depends on latitude and varies by month. Coefficient of reflectance is very influential on evapotranspiration. Table 5 contains the value of the reflection coefficient used in Method Mock.

2. Actual Evapotranspiration

Evapotranspiration that occurs in conditions of limited water available is called actual evapotranspiration. It is influenced by the proportion of exposed surface (m) in the dry season. The amount of **m** for each region is different. Mock classified **m** into three regions with each exposed surface values shown in Table 6, respectively.

Actual evapotranspiration is also influenced by intensity of rainy days (n) in a month. The ratio between the difference of potential evapotranspiration and actual evapotranspiration to potential evapotranspiration is affected by the exposed surface (m) and number of rainy days (n), as shown in the following formulation:

$$\frac{\Delta E}{Ep} - \left(\frac{m}{20}\right)(18-n)$$

So

$$\Delta E = Ep\left(\frac{m}{20}\right)(18-n)$$

Actual evapotranspiration is the evapotranspiration that is actually happening, and calculated as follows:

Ea = EP - ΔE

***Water Surplus***

Water surplus is precipitation that directly effected on infiltration, percolation, and total run-off into soil storage (SS). Water surplus (WS) formula is shown as follows:

WS = (P - Ea) + SS

Soil moisture storage (SMS) consists of the capacity of the soil moisture (SMC), infiltration zone, surface run-off, and soil storage (SS). Range of SMC value in region depends on the type of land cover and soil types. Soil moisture storage is calculated as follows:

SMS = ISMS + (P - Ea)

where

ISMS = initial soil moisture storage (initial soil moisture reservoir), a soil moisture capacity (SMC) or soil moisture capacity of the previous month.

P-Ea = precipitation that has undergone evapotranspiration.

There are two conditions to determine the SMC:

a) SMC = 200 mm/month (assumption), if P - Ea> 0. If SMS reached or exceeded its maximum capacity, water will not be stored in the moist soil. It means that soil storage (SS) equals to zero and the amount of water equals to the surplus P - Ea.

b) SMC = SMC in previous month + (P - Ea), if P - Ea <0.

In this situation, if soil moisture reservoir did not reach maximum capacity, water will be stored in the moist soil. The amount of stored water equals to P - Ea. WS will be infiltrating and running off from the surface. This occurrence depends on the amount of infiltration coefficient.

***Total Runoff***

Infiltration is water surplus (WS) that multiplied by the coefficient of infiltration (if):

Infiltration (i) = WS x if

Coefficient infiltration is determined by the condition of the porosity and the slope of catchment area. Porous soils generally have larger coefficients. Infiltration continues until it reaches groundwater storage (GS). GS is influenced by:

a. Infiltration (i). The greater infiltration, the greater the groundwater will be stored, and vice versa.

b. Monthly flow recession factor (K), is the proportion of previous month's remaining groundwater. The K values tend to be greater in wet season.

c. Previous month's GS (GSPM). This value is assumed to be constant in a closed-cycle during yearly timescales. So, value of GSPM in the first month must be made equally to value of the last month of a year.

So then, Mock formulated groundwater storage as follows:

GS = {0.5 x (1 + K) x i} + {K x GSPM}

ΔGS during the annual timescales is always zero, (e.g. for 1 year):

$$\sum_{i-month1}^{month-n} \Delta GS = 0$$

ΔGS is the difference between the amounts of water stored in the soil is reviewed with the previous month. Change in GS is essential for the formation of river base flow (BF). BF is the difference between infiltrations BF (i) and the change of GS,

BF = i - ΔGS

Notice if ΔGS value in a month is negative (GS value of this month is less than GS value in the previous month), the value of BF will be greater than infiltration. Since water balance is a closed cycle with an annual period (e.g. 1 year) then change ΔGS in 1 year must be zero. So, BF value in a year will be equal to the amount of infiltration.

The other important debit component to be considered is a direct run-off (DRO) or surface run-off. DRO yielded from infiltration process that excess as water surplus:

DRO = WS - i

The last component of the discharge is storm runoff (SRO), which directly overflow into the river during heavy rains. SRO is considered to be calculated when precipitation is less than maximum value of soil moisture capacity. Percent of rainfall into runoff (PF) influences SRO which has range of 5% - 10%, and in some particular cases it could be increasing up to 37.3%.

If precipitation (P) > maximum soil moisture capacity, SRO = 0. If P < maximum soil moisture capacity, SRO is precipitation multiplied by the PF, or SRO = P x PF. Thus, the TRO is an accumulation of several components of river discharge:

TRO = BF + DRO + SRO

TRO value is expressed in mm/month, or in discharge rate, $m^3$/sec if multiplied by the catchment area in $km^2$.

## RESULTS AND DISCUSSION

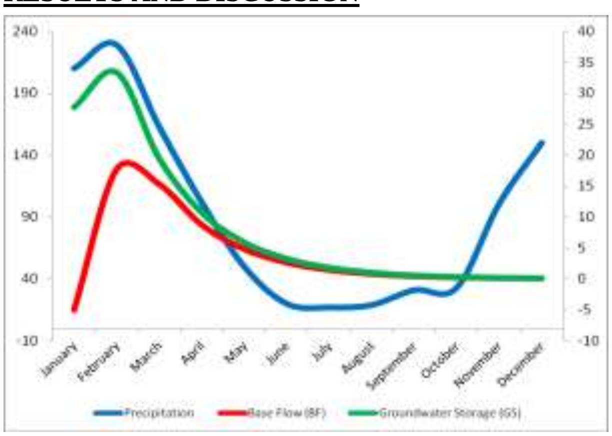


*Figure 8: Time series of rainfall, groundwater storage and base flow.*

DRO, GS, and BF are influenced by precipitation pattern. Meanwhile the actual evapotranspiration tends to be stable throughout the year, ranging from 134-239 mm/month. Ea is only affected by temperature and solar radiation that tend to be invariable every year.

Total groundwater storage of 10.24 $km^2$ catchment area was 1,066,332,658.23 L/year, meanwhile the total need of steam mass flow rate is 2.44 kg/s or 7,086,136,900.76 L/year.

Mass balance of the Atadei reservoir deficits 6,019,804,242.53 L/year. These conditions will affect the supply of groundwater to the Atadei geothermal reservoir, so that the recommendations to maintain the reservoir on a long term economical periods should be considered. Artificial recharge, reinjection management, and desalination of brine waters are example suggestions.

## CONCLUSION

Water balance calculations using method F. J. Mock is a reasonably good approximation. Those calculations successfully tested a preliminary interpretation of the boundaries in semi-arid area of 10.24 $km^2$ that can only produce 1 billion liters of water for a year.

Deficiency of Atadei mass balance reservoir come about from assumption that total groundwater storage from water balance calculation is only obtained from surface water.

Calculation of ground water potential is not reflected the actual conditions of the research areas, because the data is very narrow and needs to be integrated with detailed geology, geochemistry, geophysics, and drilling surveys. Additional hydrogeology analysis such as slope data, soil type, land cover, and stable isotope will greatly assist the interpretation of recharge zone in the further study.

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*Table 2: Average climatological data in Wai – Oti Maumere Meteorology Station (1973 – 1990).*

| **Month** | **RH (%)** | **S (%)** | **t (°C)** | **W (km/hari)** | **W (mile/hari)** | **CH (mm)** |
|---|---|---|---|---|---|---|
| January | 86 | 38.25 | 27.45 | 7.52 | 4.67 | 210 |
| February | 88 | 40.32 | 27.25 | 8.84 | 5.49 | 229 |
| March | 86 | 43.65 | 27.6 | 9.44 | 5.86 | 163 |
| April | 83 | 44.46 | 27.9 | 9.03 | 5.61 | 102 |
| May | 77 | 48.33 | 27.65 | 13.10 | 8.14 | 50 |
| June | 74 | 47.7 | 27.05 | 16.48 | 10.24 | 20 |
| July | 72 | 51.12 | 26.8 | 16.10 | 10.00 | 17 |
| August | 71 | 53.91 | 27.1 | 15.15 | 9.42 | 19 |
| September | 73 | 55.8 | 27.8 | 12.34 | 7.67 | 31 |
| October | 75 | 57.87 | 28.4 | 16.88 | 10.49 | 33 |
| November | 81 | 47.52 | 28.4 | 15.63 | 9.71 | 101 |
| December | 85 | 43.56 | 28.2 | 10.39 | 6.46 | 150 |

*Table 3: Mean temperature vs evapotranspiration parameters A, B and Ea.*

| **Temperature (°C)** | **8** | **10** | **12** | **14** | **16** | **18** | **20** | **22** | **24** | **26** | **28** | **30** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **A (mmHg/°F)** | 0.304 | 0.34 | 0.39 | 0.43 | 0.48 | 0.54 | 0.6 | 0.67 | 0.75 | 0.83 | 0.92 | 1.01 |
| **B ($mmH_2O$/hari)** | 12.6 | 12.9 | 13.3 | 13.7 | 14.8 | 14.5 | 14.9 | 15.4 | 15.8 | 16.2 | 16.7 | 17.1 |
| **Ea (mmHg)** | 8.05 | 9.21 | 10.5 | 12 | 13.6 | 15.5 | 17.5 | 19.8 | 22.4 | 25.2 | 28.3 | 31.8 |

*Table 4: Solar radiation value on atmosphere horizontal surface (mm/day).*

| **Month** | **Jan** | **Feb** | **Mar** | **Apr** | **May** | **Jun** | **Jul** | **Aug** | **Sep** | **Oct** | **Nov** | **Dec** | **Year** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **5° N** | 13.7 | 14.5 | 15 | 15 | 14.5 | 14.1 | 14.2 | 14.6 | 14.9 | 14.6 | 13.9 | 13.4 | 14.39 |
| **0°** | 14.5 | 15 | 15.2 | 14.7 | 13.9 | 13.4 | 13.5 | 14.2 | 14.9 | 15 | 14.6 | 14.3 | 14.45 |
| **5° S** | 15.2 | 15.4 | 15.2 | 14.3 | 13.2 | 12.5 | 12.7 | 13.6 | 14.7 | 15.2 | 15.2 | 15.1 | 14.33 |
| **10° S** | 15.8 | 15.7 | 15.2 | 13.8 | 12.4 | 11.6 | 11.9 | 13 | 14.4 | 15.3 | 15.7 | 15.8 | 14.21 |

*Table 5: Coefficient of Reflectance ( r).*

| No. | Surface | (r) |
|---|---|---|
| 1 | Earth's average surface | 40% |
| 2 | Fresh snow drops fall in the last season | 40-85 % |
| 3 | Species of desert plants with hairy leaves | 30-40 % |
| 4 | Dry and tall grass | 31-33 % |
| 5 | Desert surface | 24-28 % |
| 6 | Plants overshadowed the entire surface | 24-27 % |
| 7 | Young plants overshadowed the entire surface | 15-24 % |
| 8 | Seasonal forest | 15-20 % |
| 9 | Farm fruit forest | 10-15 % |
| 10 | Dry bare soil | 12-16 % |
| 11 | Bare soil moist | 10-12 % |
| 12 | Wet bare soil | 8-10 % |
| 13 | Wet-dry sands | 9-18 % |
| 14 | Clean water with sun elevation $45^o$ | 5% |
| 15 | Clean water with sun elevation $20^o$ | 14% |

*Table 6: Exposed surface, m.*

| No. | m | Area |
|---|---|---|
| 1 | 0% | Primary, secondary forest |
| 2 | 10-40 % | Eroded zone |
| 3 | 30 50 % | Farmland |

*Table 7: Water balance result.*

| Month | Ea(mm/month) | I (mm/month) | Gs (mm) | ΔGs | BF | DRO | Gs (L) @ 10,24 $km^2$ |
|---|---|---|---|---|---|---|---|
| January | 134.68 | 22.60 | 27.71 | 27.62 | -5.02 | 52.72 | 283,705,845.76 |
| February | 151.19 | 23.34 | 33.33 | 5.62 | 17.72 | 54.47 | 341,294,836.27 |
| March | 158.22 | 1.44 | 19.44 | -13.89 | 15.32 | 3.35 | 199,103,709.35 |
| April | 178.47 | 0 | 10.69 | -8.75 | 8.75 | 0.00 | 109,507,040.15 |
| May | 191.20 | 0 | 5.88 | -4.81 | 4.81 | 0.00 | 60,228,872.08 |
| June | 147.54 | 0 | 3.23 | -2.65 | 2.65 | 0.00 | 33,125,879.64 |
| July | 158.78 | 0 | 1.78 | -1.46 | 1.46 | 0.00 | 18,219,233.80 |
| August | 176.65 | 0 | 0.98 | -0.80 | 0.80 | 0.00 | 10,020,578.59 |
| September | 187.87 | 0 | 0.54 | -0.44 | 0.44 | 0.00 | 5,511,318.23 |
| October | 239.94 | 0 | 0.30 | -0.24 | 0.24 | 0.00 | 3,031,225.02 |
| November | 198.85 | 0 | 0.16 | -0.13 | 0.13 | 0.00 | 1,667,173.76 |
| December | 175.54 | 0 | 0.09 | -0.07 | 0.07 | 0.00 | 916,945.57 |
| **Annual Mean** | **2098.93** | **47.37** | | **0.00** | **47.37** | **110.54** | **1,066,332,658.23** |