RELATIONSHIP BETWEEN RAINFALL INTENSITY AND GROUND-WATER MOVEMENT IN SUBFLUVIAL AQUIFERS

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1. Foreword

The way waters infiltrate and percolate through permeable grounds notably vary according to whether the aquifers do not depend upon surface waters or are laying near or under these.

In the first case the feeding of the aquifer is performed directly from storm on the surface of the ground, eliminating the water removed by runoff and evapotranspiration and that one retained in the unsaturated soil.

In the instance of side feeding of an aquifer from a sheet of water, the only foreseen losses are those due to evapotranspiration, when the level of the water table is so much elevated as to reach with its capillar fringe the most superficial part of the ground (1). Such loss is also null when the water table is fed from up above, as it is the case of subfluvial aquifers.

A particular instance occurs along torrentlike rivers, when the superficial water flow concerns only a narrow part of the river bed or when, during the dry period, it is quite come to an end.

When the alluvium lays on impermeable soil, we have therefore an example of independent monodirectional water table, fed by infiltration of the surface flow and by the rainfalls occurred on the alluvium.

The lateral feeding is therefore negligible, since the impermeable surface of the grounds nearby, only partly covered by a modest cover of vegetal soil, allows only a quite negligible hypodermal transversal flow (2).
2. Subfluvial Flow

The direct action of rainfalls, compared to that of the water running on the surface in feeding the subfluvial water above mentioned, may be considered negligible. Therefore the zone of infiltration is reduced only to the streamflow width, along with all the river as far as this has the least minimum surface flow (3).

In such a case, the infiltration seems to be dependent by the hydric level and flow of the river; it takes place, besides, according to the ways going far off those phreatic waters as long as the charge of the surface water flow increases (4) thus becoming more and more intense together with the increase of the streamflow width.

Such circumstances generally seem to be connected to the increase of rivers flow, though the infiltration is efficient only when the surface water is sufficient and lasts long, enough to afford the seepage in the alluvium until its saturation, and the consequent percolation, as far as the underlaying water table. The surface water, therefore, must be enough so as to afford the field capacity and feed the capillary fringe and the subfluvial aquifer. (5).

Along such a dimensional pattern the water penetrates vertically as far as the hydrostatic surface, following thereafter a diverging path towards the valley owing to permeability, effective infiltration and water table slope, then following it along a parallel path as far as the infiltration ceases.

In the instance of torrent beds, the slope and the permeability are frequently notable, since the subfluvial aquifer flow often reaches very high values.

In such cases the variation of subfluvial flows is not influenced by the rains fallen on the alluvium, but by the rainfalls concerning the catchment basin and their action in the arising of streamflow.

The action exerted by rainfalls on subfluvial flow seems more uncertain than in normal phreatic waters, and it is still obscure the role held in such phenomena by intensity, frequency and duration of storms.

The influence of such factors of subfluvial aquifers feeding is at last still more complicated because of their previous conditioning of surface circulation and streamflow.

3. Survey Programme

Some studies performed on the influence exerted by rainfalls on aquifers showed that some satisfactory correlations can be obtained if acting on the medial values of long periods (6,7) and that such correlations are less good when considering the seasonal rainfalls or those of a shorter period of time (8). It was instead very useful to investigate about a correlation between the aquifers and the rainfalls of each storm.

In the instance of subfluvial water tables, besides the general interest the problem offers, a correlation of this kind would offer notable uses, as the forecast for hydric disponibilities in connection to both the answer time of the aquifer and the available flow.

According to Goldschmidt (9), who studied the problem in a climatic environment not very dissimilar from the one surveyed in this study, the feeding of the aquifer would be ruled by the relation

\[ R_u = \alpha (P - P_0) \]

wherein
\( \alpha \geq 1 \) is a dimensionless coefficient characteristic of the catchment basin of the water table;

\( P \) annual precipitations on the basin;

\( P_0 \) Precipitations limit, characteristic of the basin.
Moreover, so as to obtain some less uncertain correlations about each storm, it
seems useful to evaluate the precipitation quantity that, drain away owing to runoff,
has nothing to do with the feeding of the water table. All this owing to the fact that
the exceeding part of afflux is eliminated on the runoff or evaporation.

There is therefore a precipitation intensity threshold beyond which it less and less
influences the aquifer.

It is our aim therefore to investigate experimentally such a value by substracting
to each precipitation all that is excessive in relation to determinated values of the thresh-
hold, and try to find the value owing to which the obtained affluxes influence better
the aquifer (10).

4. EXPERIMENTAL APPLICATION

For the study we wish to explain that we have used the data elaborated by
Pirozzi and Gulli (12) on the basis of direct findings, followed thereafter by the author.
To such a purpose, four catching works of subfluvial water already existant have
been used.

They arc located in southern Calabria (Italy) in the alluviums of the Novito,
Torbido and Tuccio torrents. This last along its terminal course is better known as
Fiumara of Melito, or simply Melito.

The subfluvial catching of the Novito is situated at a countryside called Oliveto,
40 m a.s.l., and is constituted by a filtering tunnel 85 m long; it is transversal to the
alluvial bed at a depth of about 7 m, and is fed by a catchment basin of 51 km². This
basin is characteristically marked by mountainous tracts of strong slope and is formed
by prevalently impermeable soil.

The catching of the Torbido is situated in a countryside called Zinni and is formed
by a filtering tunnel parallel to the water course, draining the water along 280 m. It
has been excavated into alluvium sideways of the torrent bed, and a depth which
varies from 5 to 12 m. The tributary catchment basin is 77 km², of which about 68 %
is made of impermeable soil.

Along the bed of Tuccio there are the two last subfluvial catching here considered :
the upward one is located near the Jelasi bridge, 380 m a.s.l., the other is situated at
Musoponiti, where the torrent is called Melito.

The catching near Jelasi bridge is constituted of a concrete barrage into the allu-
vium 100 m large and deep more than 14 m to the impermeable geological bed.

The subfluvial catching of Melito at Musoponiti is instead furnished with a drain-
ing tunnel 235 m long located in the bed and running parallel to the water course, at
a variable depth between 5 and 11 metres.

The Tuccio watershed, or Melito one, is prevalently impermeable and is constitu-
ted of gneiss and fundamental mica schist, that form the structure of a catchment
basin marked with sloping and abrupt valleys. These descend abruptly from levels su-
perior than 500 m as far as the bottom of the valley where then, without any medial
phase, the valley leg of the water course begins. The torrent then snakes with minor
slopes towards the sea wandering here and there through a large and deep alluvial bed.

The granulometry of the material is scarcely variable in connection to the depth
of alluvium and is particularly rich in sand components. This character, as it was
evidenced by the survey performed by Gulli (12), appears to be common also to the
material of the Novito and Torbido beds.

5. EXPERIMENTAL DATA

5.1. Flow

We have used the values of the flow drained for gravity in absence of whatever
obstructions. Flow had been evaluated by means of daily gauging. On the basis of
such elements we have calculated the average monthly drained flow. These values are not representative of the whole flow of the subfluvial water table, but only that amount depending on the degree of utilization realized in each catching work (13).

The trapped water may be, however, considered as an index of the water table flow in as much as it represents a variable quantity depending on it, even if they are not proportional to the total flow of the subfluvial water table.

They have been used therefore as indexes of subfluvial flow, after taking also into consideration the poor influence exerted by such substitution on the statistic application which these data underwent.

The adoption of trapped water instead of the total one cancels, by the way, the possibility of establishing a hydric balance of the water table on the basis of such findings, or an evaluation of the whole waterhead together with a forecast of the pertinent flows.

5.2. Precipitations

The afflux on catchment basins, tributary to the subfluvial water table investigated has been obtained by the precipitations observed at the raingauges located on each of them.

For each raingauge we have calculated the monthly amount of rain. We have assumed as average monthly precipitation on the basin the average of the observed monthly precipitations at the raingauges of that basin.

Such average value may be considered variable together with the real precipitation on the watershed and it may therefore be considered a representative indication of it.

For a further elaboration it was then necessary to dispose of the monthly amount of the precipitations on the basin, with the exclusion of all those quantities of rain exceeding, during each event, determined values of precipitation.

This evaluation could not be made easily without a simplification of the calculation. We have therefore reviewed each daily precipitation observed at each raingauge and have eliminated the amounts exceeding these values of precipitation (in mm): 50, 30, 20, 15, 10, 5 and 1.

The average of the monthly totals thus obtained at each raingauge of each basin has been used as indication of the monthly precipitation for that specific basin, not exceeding the above said precipitation limits at each storm.

We think that the simplification already shown afforded a quite good representation of the natural phenomenon especially for the elevated values of the pluviometric threshold, in as much as it happens very rarely that during the same day a higher precipitation may observed. The approximation of the method seems to be lesser in relation to the diminishing of the value of the pluviometric threshold, and when this value is equal to 1 mm, the average monthly precipitation is represented by a value very similar to the number of the rain days observed during the month.

As indication of the diminution created by eliminating the quantity exceeding the above mentioned precipitation limits, we have reported at fig. 1 the real monthly average precipitations for the Novito basin, and the pertinent values purified as we have already indicated. In the same figure we have also reported the flows drained from the subfluvial water table of the Novito at Oliveto, at a two month’s interval in the drawing so as to evidence their correlation with the precipitations.

Finally, so as to find also that quantity of precipitation which does not influence the aquifer, since it is dispersed owing to evapotranspiration or retained by the unsaturated strata of soil, we have subtracted from daily precipitations all those quantities inferior or equal to particular limit values, which we have put equal to 5 and 10 mm in this study.

Since such proceeding did not afford any notable result in the instances already examined, we have limited them to the basin of Jelasi bridge.
Fig. 1 — Novito at Oliveto: Fluctuations of monthly ground water flow and monthly rainfall purged by daily rain exceeding pluviometric thresholds.
6. ELABORATION OF DATA

The data preparation was performed so as to able to evidence at the same time
1) according to which value of the daily pluviometric threshold do the monthly precipitation on the basin result to be better correlated to the flow of the subfluvial water table, on the basis of such purified value;
2) with what delay of the flows as regard as the precipitations, are these better connected to the precipitation of n° 1).
To such a purpose, by means of a considerable series of statistical applications, we have calculated the Bravais’ coefficient of correlation between the average monthly flow and the precipitation not exceeding daily the various values of the pluviometric treshold. We have calculated such correlations for each one of the four ground water under study and for phase shifts between flows and precipitations varying between zero and six months.
Similar correlations have been obtained between flows and unpurified precipitations, and finally between flows and precipitations depurated both of daily amounts of rain superior than 15 mm and those inferior than 5 and 10 mm.
Calling:

\[Q\] average flow drained monthly from subfluvial aquifer;
\[Q_p\] flow \(Q\) of \(p\) months following the precipitation \(P\);
\(P\) monthly precipitation on the tributary catchment basin;
\(P_d\) precipitation \(P\) depurated of the exceeding daily precipitation as regards as \(d\);
\(d\) pluviometric threshold per day, equal 50, 30, 20, 15, 10, 5 and 1 mm;
\(p\) delay in month between \(P\) and \(Q\);
\(n\) freedom degrees of the system;

The coefficient of correlation \(r_{PQ(d_p)}\) has been calculated by the expression:

\[
r_{PQ(d_p)} = \left[ \frac{\Sigma P_d Q_p - (\Sigma Q_p)(\Sigma P_d)}{n} \right] \left[ \left( \frac{\Sigma Q_p^2}{n} - \frac{(\Sigma Q_p)^2}{n} \right) \left( \frac{\Sigma P_d^2}{n} - \frac{(\Sigma P_d)^2}{n} \right) \right]^{-1/2}
\]

The freedom degrees \(n\) resulted different for the application of the various basins, because of the number of the data at disposal, that is to say, of the observation’s duration. The periods of observation referred to the used findings are:
Novito at Oliveto: from Jan. 1949 to Dec. 1954 (months 72)
Torrido at Zinni: from Oct. 1951 to Nov. 1954 (months 38)
Tuccio at Jelasi: from Aug. 1948 to Dec. 1960 (months 130)
Melito at Musoponiti: from Oct. 1948 to Dec. 1954 (months 75)
On those instances when the correlation was particularly high we also calculated the coefficient of regression by the expression:

\[
h_{PQ(d_p)} = \left[ \frac{\Sigma P_d Q_p - (\Sigma Q_p)(\Sigma P_d)}{n} \right] \left[ \frac{\Sigma P_d^2}{n} - \frac{(\Sigma P_d)^2}{n} \right]^{-1}
\]

7. STUDY FINDINGS

The numerous calculated coefficient of correlation permitted us to know for each one of the four subfluvial aquifers under examination the ways those coefficients varied both in connection to the phase shift of the flows as regard as the precipitations, and in function of the value of the pluviometric treshold.
The correlation coefficient that were mostly indicative have been reported on the table 1 and 2, and they may be noticed by the graphics of figure 2 and 3, that are particularly pertinent to the correlations between the flow and the precipitations with a phase shift of 2 and 3 months.

The coefficients regarding some determinated levels of the pluviometric threshold were on such cases particularly high since they reached the highest value of 0.777. This value is to be referred to the correlation extant between the precipitation of the Torbido basin depurated of all exceeding quantities pertinent to the threshold of 5 mm and the flows of the subfluvial aquifer of that torrent, caught with a delay of two months.

The same coefficient became instead 0.760, owing to a delay of one month, and 0.551 for a delay of three months.

It would have been interesting to evaluate then the correlation coefficient for the medial phase shifts between one and two months. In fact in the instance of the low Durance water table, in France, even if acting on average monthly values, some very interesting findings have been obtained delaying of 20 days the streamflow as regard to the water table level (14).

### TABLE 1

Coefficients of correlation between monthly precipitations not exceeding daily pluviometric threshold and subfluvial flows/delay of two months.

<table>
<thead>
<tr>
<th>Pluviometric threshold</th>
<th>Novito</th>
<th>Torbido</th>
<th>Tuccio</th>
<th>Melito</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 mm/day</td>
<td>0.344</td>
<td>0.459</td>
<td>0.400</td>
<td>0.420</td>
</tr>
<tr>
<td>30 mm/day</td>
<td>0.508</td>
<td>0.621</td>
<td>0.502</td>
<td>0.582</td>
</tr>
<tr>
<td>20 mm/day</td>
<td>0.519</td>
<td>0.648</td>
<td>0.514</td>
<td>0.639</td>
</tr>
<tr>
<td>15 mm/day</td>
<td>0.521</td>
<td>0.665</td>
<td>0.590</td>
<td>0.645</td>
</tr>
<tr>
<td>10 mm/day</td>
<td>0.523</td>
<td>0.655</td>
<td>0.607</td>
<td>0.671</td>
</tr>
<tr>
<td>5 mm/day</td>
<td>0.516</td>
<td>0.633</td>
<td>0.619</td>
<td>0.670</td>
</tr>
<tr>
<td>1 mm/day</td>
<td>0.515</td>
<td>0.777</td>
<td>0.640</td>
<td>0.637</td>
</tr>
</tbody>
</table>

### TABLE 2

Coefficients of correlation between monthly precipitations not exceeding daily pluviometric threshold and subfluvial flows/delay of three months.

<table>
<thead>
<tr>
<th>Pluviometric threshold</th>
<th>Novito</th>
<th>Torbido</th>
<th>Tuccio</th>
<th>Melito</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 mm/day</td>
<td>0.275</td>
<td>0.477</td>
<td>0.414</td>
<td>0.508</td>
</tr>
<tr>
<td>30 mm/day</td>
<td>0.359</td>
<td>0.536</td>
<td>0.447</td>
<td>0.596</td>
</tr>
<tr>
<td>20 mm/day</td>
<td>0.357</td>
<td>0.522</td>
<td>0.557</td>
<td>0.571</td>
</tr>
<tr>
<td>15 mm/day</td>
<td>0.356</td>
<td>0.519</td>
<td>0.587</td>
<td>0.622</td>
</tr>
<tr>
<td>10 mm/day</td>
<td>0.355</td>
<td>0.496</td>
<td>0.592</td>
<td>0.634</td>
</tr>
<tr>
<td>5 mm/day</td>
<td>0.350</td>
<td>0.498</td>
<td>0.611</td>
<td>0.659</td>
</tr>
<tr>
<td>1 mm/day</td>
<td>0.326</td>
<td>0.551</td>
<td>0.626</td>
<td>0.624</td>
</tr>
</tbody>
</table>

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It was impossible for the case just examined to perform such a calculation as the necessary values of the subfluvial flow were not always at disposal.

A judgement on the significance of the coefficient of correlation may be expressed comparing that coefficient with the significance threshold, which for the cases studied here assumes the following values (19):

- Novito at Oliveto: \( n = 70; 5\% = 0.235; 1\% = 0.306 \)
- Torbido at Zinni: \( n = 36; 5\% = 0.329; 1\% = 0.424 \)
- Tuccio at Jelasi: \( n = 128; 5\% = 0.183; 1\% = 0.238 \)
- Melito at Musoponiti: \( n = 73; 5\% = 0.230; 1\% = 0.300 \)

We must notice therefore that the correlations studied for phase shifts of 2 or 3 months are all highly significant, which means that the calculated coefficients are significantly different from zero.

About those values that correspond to 0.05 of probability, and which therefore are not significantly different from zero, we must observe that the values obtained as phase shifts and various depurations have a tendency to cancel according to ordered series having significant and evident tendency. That, even for these cases, may lead one to consider the findings less casual.

Moreover, the heterogeneous error that effects the single coefficients of correlation does not allow in such cases an easy application of the analysis of the variance, which by the way, would be of secondary interest for the lowest values of the correlation coefficients.
Fig. 3 — Correlation between monthly precipitations not exceeding daily pluviometric threshold and subfluvial flows: Delay of three months.

From a general point of view it seems that in case of scarcely permeable soils, the best correlations are possible with low values of the pluviometric threshold and that the contrary happens for more permeable soils. Such a character finds a confirmation in the findings of this study: in fact after our experimentations on basins particularly impermeable, the most significant coefficients have been obtained by the correlations regarding the precipitations depurated of the exceeding quantities in connection to pluviometric threshold between 1 and 15 mm. With this increase of the value of the threshold, the correlation coefficients became sensibly inferior reaching a minimum value when we acted on the effective precipitations without any depuration.

Such diminution of the coefficients became so much more marked as more elevated where the most significant coefficients and the relative pluviometric threshold were better individualized.

The correlation coefficient calculated on the basis of the precipitations depurated both of the quantity exceeding the values of the pluviometric threshold and that inferior to determined minimum levels did not come out particularly indicative.

Even if they are highly significant, they are inferior to those obtained for precipitations not depurated of the values beneath the inferior threshold. In the case of Tuccio at Jelasi, for phasing of three months, the correlation coefficients relative to precipitations not exceeding 15 mm were equal to 0.592; those relative to precipitations between 10 and 15 mm were equal to 0.510 and those relative to precipitations between 5 and 15 mm were 0.549.

All characteristics we have illustrated until now depend on the number and the interaction of the various geohydrologic elements exerting their influence on the phenomenon.
As far as the Novito basin is concerned, in as much as the correlations kept themselves less dependent on the values of the pluviometric threshold, our investigation has been extended to all the correlation coefficients concerning phase shifts between 0 and 6 months, thus obtaining the values reported at table 3.

![Graph](image.png)

**Fig. 4** — Novito at Oliveto: Coefficients of correlation between monthly precipitations not exceeding daily pluviometric threshold and subfluvial flows in delayed shifts from 0 and 6 months.

As it is showed by the graphics of figure 4, the values that are significantly different from 0 more than 0.05 and 0.01 of probability, are referred to phase shifts of 1, 2 and 3 months. The correlations between contemporaneous values of afflux and downflow or out of phase of 4, 5 and 6 months have resulted instead to be inferior than such limits of significance.

It has been also noticed that with the increase of the pluviometric threshold the correlation coefficient was found to be decreasing in the case of minor pha-
se shifts, and that they increased together with the increase of the phase shifts months. It is our opinion that in such cases the correlation coefficient, still low and less significant, has evidenced the correlation between the rainy seasons afflux and the aquifers exhaustion downflow.

**TABLE 3**

| Novito at Oliveto: coefficients of correlations between monthly precipitations not exceeding pluviometric threshold and subfluvial flows in delayed shifts from 0 and 6 months |

<table>
<thead>
<tr>
<th>pluviometric threshold</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 mm/day</td>
<td>0.132</td>
<td>0.453 ++</td>
<td>0.344 ++</td>
<td>0.275 ++</td>
<td>0.226 ++</td>
<td>0.159 ++</td>
<td>0.070</td>
</tr>
<tr>
<td>30 mm/day</td>
<td>0.183</td>
<td>0.517 ++</td>
<td>0.508 ++</td>
<td>0.359 ++</td>
<td>0.235 ++</td>
<td>0.137 ++</td>
<td>0.025</td>
</tr>
<tr>
<td>20 mm/day</td>
<td>0.244</td>
<td>0.530 ++</td>
<td>0.519 ++</td>
<td>0.357 ++</td>
<td>0.213 ++</td>
<td>0.095 ++</td>
<td>0.018</td>
</tr>
<tr>
<td>15 mm/day</td>
<td>0.219</td>
<td>0.536 ++</td>
<td>0.521 ++</td>
<td>0.356 ++</td>
<td>0.205 ++</td>
<td>0.072 ++</td>
<td>0.014</td>
</tr>
<tr>
<td>10 mm/day</td>
<td>0.230</td>
<td>0.533 ++</td>
<td>0.523 ++</td>
<td>0.355 ++</td>
<td>0.203 ++</td>
<td>0.064 ++</td>
<td>0.012</td>
</tr>
<tr>
<td>5 mm/day</td>
<td>0.218</td>
<td>0.515 ++</td>
<td>0.516 ++</td>
<td>0.350 ++</td>
<td>0.182 ++</td>
<td>0.038 ++</td>
<td>0.005</td>
</tr>
<tr>
<td>1 mm/day</td>
<td>0.235</td>
<td>0.525 ++</td>
<td>0.515 ++</td>
<td>0.356 ++</td>
<td>0.157 ++</td>
<td>0.016 ++</td>
<td>0.003</td>
</tr>
</tbody>
</table>

Sometimes the values of the correlation coefficients did not fall into the same line along a quite definite curve varying the pluviometric thresholds, but showed as regards this curve quite sensible shifts.

Yet the general performance was a quite definite one, for the majority of the cases, even when the period of disposable data was not such to keep the shift of the correlation coefficients within limits sufficiently modest.

An idea on the real influence of the precipitations fallen on the basins, opportunely depurated, on the relevant captured subfluvial flows may be obtained, even if of quite indicative value, by the regression coefficient hereafter, that were obtained for the cases under investigation.

They have been calculated for each of them according to the phase shift and depuration conditions for which had been obtained the most elevated correlation coefficient.

Recalling the symbols already mentioned, the following values have been obtained hereafter expressed in l/sec./mm:

- Novito at Oliveto: \( b_{PQ(0,1)} = -0.1269 \)
- Torbido at Zinni: \( b_{PQ(5,2)} = -2.6762 \)
- Tuccio at Jelasi: \( b_{PQ(1,2)} = 3.2802 \)
- Melito at Musoponiti: \( b_{PQ(10,2)} = 0.5442 \)

One could also pass from such values, after evaluating the efficiency of the catching works, to the evaluation of the aquifers flow and make some forecasts on the basis of the precipitations on the watershed.

To such a purpose and with the aim of obtaining a better precision from the evaluations, it would seem worth while extending the research to the multiple correlations.
between the subfluvial flow and the precipitations of the various precedent months, depurating each of them according to different pluviometric thresholds, in connection to the different action they exert in the feeding of the aquifers.

In such a manner one could think about the separation of the subfluvial aquifer's feeding performed directly by the river bed from that depending on the hypodermal circulation of the catchment basin and on the exhaustion of the superficial existing water tables.

Since we may obtain similar findings for catchment basins having a different permeability, it seems possible, by the way, to study the characteristics of the aquifers in connection to the various geomorphological and hydrological elements of the relevant feeding basins.

REFERENCES