

Recent low-flow and groundwater storage changes
in upland watersheds of the Kanto region, Japan

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Abstract. Annual trends in baseflow and groundwater storage over the past 40 years are deduced from low flow observations in four upland catchments in the northern parts of the Kanto region. These catchments are part of the water supply system for the Greater Tokyo metropolitan area, and groundwater constitutes an integral component of their storage capacity. While the data exhibit great variability from year to year, no evidence was found that any persistent or systematic groundwater storage changes have taken place in this region over the period of record.

CE Database subject headings: Climatic changes; Hydrologic Data; Ground water; Water storage; Base flow; Japan

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1. Introduction

In recent years there has been a growing public awareness that human activities in the present industrial era have been exerting a powerful influence on the global climate. The fact, that atmospheric concentrations of carbon dioxide, methane and nitrous oxide have been increasing, has led to the consensus (e.g. IPCC, 2007) that globally this has resulted in radiative forcing and in an average net warming effect over the past century. While indications abound that this warming is real, the resulting changes in hydrologic cycle activity and water resources are more indeterminate and unsettled. This is certainly the case for the Japanese archipelago. For instance, along the Pacific Ocean side of Honshu the average annual temperature has been increasing at a rate of about 0.11°C per decade (Japan Meteorological Agency, 2005) to 0.14°C (Yue and Hashino, 2003a) since the early 1900's. Incidentally, this is very close to the global average land surface temperature trend over the same period (e.g. Jones et al., 1999). Increasing temperatures would normally be expected to produce a more humid environment and an accelerating hydrologic cycle, but the available records are not unequivocal in this. Several measures suggest indeed a more active hydrologic cycle; the number of heavy daily precipitation events has been reported to be on the increase over the past century (Iwashima and Yamamoto, 1993), and as an indication of a more humid landsurface environment, landscape evapotranspiration appears to have been increasing over the past half century as well (Asanuma et al., 2004; Brutsaert, 2006). On the other hand, the average monthly and yearly precipitation was shown to have decreased significantly during the past century over major portions of Japan by Yue and Hashino (2003b); for instance, for the side of the country adjacent to the Pacific, they calculated an average yearly trend of -11.8 percent over the period 1896-1996. In addition, their analysis showed that while heavy rainfall events were becoming more severe in the rainy season, the severity of droughts during the dry season had also been increasing; this led these authors to conclude that, if these trends were to persist, increasingly severe water shortage problems could be expected in the future, especially on the Pacific Ocean side. Similar results have been presented by the Japan Meteorological Agency (2005); for roughly the same area over the period of 1898-2004, the precipitation trend was reported to be -1.06 mm/10

years. In a similar vein, a study by the Ministry of Land, Infrastructure and Transport of Japan (2003) has shown that the amount of available water resources (estimated as the difference between the precipitation and evaporation) in Japan during dry periods has been decreasing steadily since the mid 1950s. For example, the lowest amount of the available water resources in 20 years for 1956-1975 was around 3×10^5 million m^3/year , and it decreased to only some 2×10^5 million m^3/year for the period of 1981-2000.

In Japan municipal and industrial water supply systems rely primarily (around 75%) on streamflow runoff in combination with surface storage reservoirs (Ministry of Land, Infrastructure and Transport of Japan, 2003). Ultimately all such runoff is derived from precipitation. Therefore, the reliability of a water supply system is often judged on the basis of past precipitation records. However, in light of the unclear and inconsistent precipitation trends over the past fifty years, considerable uncertainty remains as to the future reliability of this source of water. Moreover, even without this uncertainty, a record of past precipitation can give only an indirect picture of the water supply situation, because it represents merely one component in the water budget of a river basin. To construct a complete and accurate water budget for a catchment, all other terms beside precipitation, namely surface runoff, evapotranspiration, and the terrestrial water storage changes in the basin must also be considered. The terrestrial water storage changes consist mainly of changes in snow, soil moisture and groundwater storage; among these, basin-scale changes in groundwater storage suffer probably the largest uncertainty. Indeed, it is not easy to measure this quantity directly, so that it must usually be deduced indirectly from other measurements. The use of low flow measurements in a river for this purpose shows considerable potential (e.g. Brutsaert, 2008; Brutsaert and Sugita, 2008), but this has not been widely implemented yet.

Accordingly, as a test case, it is the objective of this paper to examine and assess the groundwater storage changes that have taken place in four unregulated upland catchments within the Tone River drainage system in the Kanto region, on the basis of the annual low flows from these watersheds. These four small river basins were selected for the practical reason, that they are part of the water supply system of Greater Tokyo (NILM-MLIT, 2003), one of the major metropolitan areas of the world, whose effective operation is critical for the wellbeing of literally tens of millions of people. In fact, all

four rivers feed reservoirs, which taken together contain some 16 percent of the total storage capacity of the Tokyo water supply system.

2. Drought Flow as an Indicator of Groundwater Storage

During periods of no precipitation or artificial inputs, the water flow observed in a river can be assumed to result primarily from drainage of groundwater from the upstream riparian aquifers in the catchment. This type of flow is commonly referred to as baseflow, low flow, drought flow, or fair-weather flow. Flows under such conditions are of practical interest because they represent the lower benchmark for run-of-the-river systems in the prediction of future water availability for water supply, river water quality during drought periods and overall basin drainage. In the present context they are mainly of interest, because they can provide an indication of the underground water storage amounts and the corresponding water table levels in the upstream contributing aquifers.

One of the more commonly used equations in hydrologic practice (e.g. Brutsaert, 2005) to describe baseflows is of the exponential decay type, namely

$$y = y_0 \exp(-t / K) \quad (1)$$

where $y = Q / A$ is the rate of flow in the stream per unit of catchment area, Q is the volumetric rate of flow in the river, A is the area of the catchment, y_0 is the value of y at the (arbitrarily) chosen reference of time, i.e. $t = 0$, and K is the characteristic time scale of the catchment drainage process, also often referred to as the storage coefficient. In the absence of recent precipitation and other input events, conservation of mass requires that storage in the catchment is related to the outflow by the following integral,

$$S = -\int_t^{\infty} y dt \quad (2)$$

in which S is the volume of water per unit catchment area stored in the upstream aquifers above the zero flow level. Performing this integration with (1) yields immediately the relationship between groundwater storage and outflow rate from the catchment, namely

$$S = Ky \quad (3)$$

Equation (3) indicates that the temporal trend of groundwater storage can be determined from the corresponding trend in baseflows observed in the catchment, that is upon taking derivatives, as follows

$$\frac{dS}{dt} = K \frac{dy}{dt} \quad (4)$$

3. Application with Drought Flow Data in the Tone River Basin

3.1 Selected Upland Catchments

Equation (4) can only be applied to catchments whose river runoff is unaffected by dams and other structures, installed to reduce peak flows and to increase low flows. The four catchments selected for the present study (Table 1) are all located upstream from large dams and the discharge data used here represent the inflow into the reservoirs behind these dams. None of the rivers has any other structures further upstream, so that the flow rate measurements can be considered to be natural and unregulated. The dam designations and the periods of record are respectively, Aimata Dam (1960-2006), Kawamata Dam (1966-2006), Yagisawa Dam (1967-2006) and Shimokubo Dam (1969-2006). The daily discharge rate and precipitation data, used in what follows, are available in part from Chugoku Construction Association (1957-1992) and from the Ministry of Land, Infrastructure and Transport (2007; personal communication, 2007).

3.2 Annual Low Flow Values

The groundwater storage in a basin goes through various high and low phases during any given year depending on the antecedent precipitation inputs over the region. Groundwater storage is not simply related to streamflow, but as (3) shows, it is directly related only to baseflow; this means that a feature of the annual baseflow record must be chosen, which can best reflect the groundwater storage during that year. Several choices can probably serve this purpose, but an objective way to track the long term evolution of this storage over many years is to monitor its lowest level each year, that is, when it reaches “rock bottom” or the non-depleted reserve, which is available for the next year. Thus, with this assumption the long term baseflow trend dy / dt to be used in (4) can in

principle be taken as the trend of the lowest daily flows for each year of the period of record. However, such individual daily flows are normally subject to error, and therefore it was decided to use the annual lowest seven-day flows, namely y_{L7} , as a more robust measure for this purpose. As an example, the lowest seven-day flows observed just upstream from the Aimata Dam reservoir are shown in Figure 1, together with the average annual flow rate in Figure 2, and the average annual precipitation in Figure 3.

3.3 Characteristic Drainage Time Scale Values

The application of (4) to determine the groundwater storage trend also requires a knowledge of the characteristic drainage time scale K . For the basins considered here, these have been determined in an earlier study by Sugiyama (1996). The technique used consisted of the construction of a master recession curve by connecting or linking the lower end parts of a number of recession hydrographs into a common curve; this master recession curve was then fitted to (1). The values derived this way were $K = 83, 71, 56, 125$ days for Aimata Dam, Kawamata Dam, Yagisawa Dam, and Shimokubo Dam, respectively. Although these values are somewhat larger than values obtained elsewhere with different methods (e.g. Brutsaert and Lopez, 1998; Brutsaert, 2008), they are used here to avoid any preconceived notion in the matter. It is worth observing that these values are strongly ($r = 0.88$) correlated with elevation, which is no doubt an indication that K is a function of elevation dependent factors, such as rock type and catchment and channel slopes, as would be expected; the linear regression is $K = -0.0966H + 150$. In any event, in the present context, the magnitude of K is of less importance, as it does not affect the sign nor the significance of the trend.

3.4 Results and Discussion

For each station, the trends of the seven-day low flows dy_{L7}/dt were first determined by simple linear regression; these values were then used in accordance with Sections 3.2 and 3.3 to derive the trends of the groundwater storage by means of the following

$$\frac{dS}{dt} = K \frac{dy_{L7}}{dt} \quad (5)$$

The results obtained this way are shown in Table 2. It can be seen that, except at Yagisawa, no trends were found to be significant at the 0.05 level. Moreover, none of the trends have consistently the same sign; thus, depending on the selected period the trends are sometimes positive and sometimes negative, and they do not show any obvious pattern of a systematic and strong increase or decrease. The trend at Yagisawa is strongly positive and significantly different from zero at the 0.05 level. However, closer scrutiny of the low flow record at this station reveals that this record appears to consist of two distinct parts, and that a marked change seems to have taken place sometime in the mid 1990's. This can be seen from the evolution of the long term trend from 1967 onward; up until 1995 the trend was still -0.294 mm/y ; after that it increased gradually and turned positive in 1999, to increase rapidly to +0.612 mm/y in 2002, and to +0.802 in 2005. This sudden increase of the low flows is somehow anomalous, because it did not occur at the other stations in the region; further investigation did not yield an obvious explanation of this anomaly, if indeed it is one and not simply a natural variation; more research will be required to clarify this issue.

While the winters in the Kanto region are generally mild, temperatures regularly go below the freezing point in the upland areas (see also Table 1 for the lowest monthly mean temperature). It is well known that whenever freezing occurs, ice near the aquifer outflow zone at the river banks can seriously affect the outflow regime there, so that the relationship between water table height and outflow rate, which is the basis of (3) and (5) used here, is no longer valid. Therefore, to decrease the possibility of ice conditions along the upstream river banks, the analysis was also carried out with the annual low flow data y_{L7} , observed during the warm season between April 1 and November 30. These results are shown in Table 3. These trends are generally somewhat smaller (and more negative) than those shown in Table 2, but otherwise they display about the same features; these are that none of them are significant and all of them show some variability depending on the selected period.

As a summary, the results of Table 2 were also averaged, by weighting them with the respective drainage areas. For the 38-year period of record common to all four stations, namely for 1969-2006, this exercise yielded an average trend of +0.253 mm/y over the total drainage area of 786 km². The relatively large positive value of this

average was due to the large value of the trend at Yagisawa; indeed at the other three stations, the trends were all negative for 1969-2006, albeit not significant.

3.5 Comparison with Trends of Related Hydrologic Variables

Finally, to put the present results also in the context of the overall water supply situation in the region, they may be compared with the trends of the average annual water inflow rates into the four reservoirs and with the recorded precipitation over the same periods. The trends of the average annual flow rates are listed in Table 4 for the four dam sites, and the those for the Aimata dam station as an example are graphically shown in Figure 2; they are strongly positive and all, except Shimokubo, are significant at the 0.05 level. Recall that the elevation of the station at Shimokubo, $H = 354$ m, is lower than the other three.

The precipitation trends at the four stations are shown in Table 5 together with Figures 3 and 4 which give example of the long-term changes of the annual precipitation for the Aimata and the Yagisawa dams. It can be seen, that all of them are positive, and except for the Yagisawa site, all are significant at the 0.05 level. For the period shown, i.e. for 1969-2006, the precipitation trend at Yagisawa is also the weakest among the four dam sites; this contrasts with the trend shown in Tables 2 and 3 for the groundwater storage changes at Yagisawa, where it is by far the largest of the four over this same period.

Inspection of the year-by-year precipitation record may also provide at least a partial explanation for the anomalous behavior of the groundwater storage trend at Yagisawa shown in Tables 2 and 3. Recall that a rather sudden increase in the annual low flow value y_{L7} was observed at that station sometime in the mid 1990's. The mean annual precipitation record at that station (Figure 4) also displays a sudden increase around the same time. However, because this abrupt increase in precipitation is not very large, this observation does not resolve the issue completely, so that further investigation is in order. In any event, these somewhat different precipitation and runoff features observed at Yagisawa, constitute merely a side issue; they do not detract in any way from the general conclusions made here regarding the hydrology of the upland Tone River catchments, but actually reinforce them.

4. Conclusions

Especially in light of the unclear and inconsistent precipitation trends over the past one hundred years, considerable uncertainty remains as to the future reliability of the current water supply systems in the country. This will require further analysis and watchful monitoring of future developments not only of precipitation and streamflow records but also of terrestrial storage changes, to gain a full understanding of the evolution of the total hydrologic budget. As part of this, groundwater storage changes at the catchment scale can be deduced from low flow observations in natural streams.

Most streams in Japan are regulated to some extent by dams and other structures, to reduce peak flows and to increase low flows; therefore, the true water supply potential of any river can only be analyzed on the basis of measurements unaffected by, and upstream from, such flow regulating structures. For the present study four catchments were selected, whose streams are unregulated and which are part of the water supply system of the Greater Tokyo area.

On the basis of the analysis performed in this study, there is no evidence that the groundwater storage in upland catchments of the Tone River has undergone persistent or systematic changes over the past forty to fifty years. This is in contrast with the average annual river flows and the annual precipitation, which have undergone marked and significant increases over this same period. Practically speaking, this means that there are no indications that there is any danger of water supply shortages for the Greater Tokyo metropolitan area in the immediate future. However, this conclusion should be tempered by the realization that a fifty-year record is relatively short, and that it will be necessary to continue to monitor the further evolution of the hydrologic budget of the upland areas carefully.

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Table 1. Characteristics of four watersheds

| Watershed | A (km ²) | H (m, ASL) | $\overline{T_a}$ (°C) | \overline{P} (mm/y) | Land use | Predominant rock type |
|-----------|---------------------------|-----------------|--------------------------|--------------------------|--|-------------------------------|
| Aimata | 110.8 | 580-2026 | 10 (-2 to 23) | 1200 | mostly deciduous forest | Tertiary Quartz Diorite |
| Shimokubo | 328.4 | 354-1979 | 15 (0 to 24) | 1000 | mixture of deciduous and coniferous trees, with a few agronomy areas near the rivers | Upper Paleozoic rocks |
| Yagisawa | 167.4 | 830-2100 | 9 (-3 to -22) | 1500 | deciduous forest | Mesozoic granite |
| Kawamata | 179.4 | 963-2967 | 7 (-4 to 20) | 1500 | mostly with coniferous forests near the divides and deciduous forests at lower elevation | Paleozoic Permian |

A : watershed area, H : elevation, \overline{P} : annual mean precipitation, $\overline{T_a}$: mean air temperature (annual value and the lowest and highest monthly means in the bracket). The lowest temperature occurs in January and highest in August. The predominant rock type is from Sugiyama (1996). Precipitation and temperature are either at dam site or at nearest meteorological station.

Table 2. Average groundwater storage trends (in mm y^{-1}), as derived from low flow measurements throughout the year in four upland catchments in the Kanto region. Asterisks indicate trend values which are significant at the 0.05 level.

| Period Dam station | 1960-2006 | 1966-2006 | 1967-2006 | 1969-2006 |
|--|-----------|-----------|-----------|-----------|
| Aimata (Tonegawa) (110.8 km^2) | -0.08110 | -0.03042 | 0.05485 | 0.09948 |
| Kawamata (Kinugawa) (179.4 km^2) | | 0.24264 | 0.25473 | 0.16908 |
| Yagisawa (Tonegawa) (167.4 km^2) | | | 0.77189* | 0.88982* |
| Shimokubo (Tonegawa) (328.4 km^2) | | | | 0.02643 |

Table 3. Average groundwater storage trends (in mm y^{-1}), as derived from low flow measurements during no-ice periods 4/01-11/30 in four upland catchments in the Kanto region. None of the values are significant at the 0.05 level.

| Period Dam station | 1960-2006 | 1966-2006 | 1967-2006 | 1969-2006 |
|---|-----------|-----------|-----------|-----------|
| Aimata (Tonegawa) (110.8 km^2) | -0.21421 | -0.14455 | -0.07568 | -0.04755 |
| Kawamata (Kinugawa) (179.4 km^2) | | 0.17269 | 0.13875 | -0.01358 |
| Yagisawa (Tonegawa) (167.4 km^2) | | | 0.33355 | 0.48533 |
| Shimokubo (Tonegawa) | | | | -0.00778 |

Table 4. Average annual river flow trends (in $\text{mm d}^{-1}\text{y}^{-1}$) for four upland catchments in the Kanto region. Asterisks indicate trend values which are significant at the 0.05 level.

| Period Dam station | 1960-2006 | 1966-2006 | 1967-2006 | 1969-2006 |
|--|-----------|-----------|-----------|-----------|
| Aimata (Tonegawa) (110.8 km^2) | 0.01703* | 0.01672* | 0.01825* | 0.02005* |
| Kawamata (Kinugawa) (179.4 km^2) | | 0.02085* | 0.02388* | 0.02293* |
| Yagisawa (Tonegawa) (167.4 km^2) | | | 0.04007* | 0.04249* |
| Shimokubo (Tonegawa) (328.4 km^2) | | | | 0.01252 |

Table 5. Average annual precipitation trends (in mm y^{-2}) measured at four upland catchments in the Kanto region. Asterisks indicate trend values which are significant at the 0.05 level.

| Period Dam station | 1960-2006 | 1966-2006 | 1967-2006 | 1969-2006 |
|------------------------|-----------|-----------|-----------|----------------------|
| Aimata | N/A | N/A | N/A | 7.25408 [†] |
| Maebashi ^{††} | 5.76797* | 6.11293* | 6.83975* | 8.39769* |
| Kawamata | | 9.04110* | 10.33536* | 11.00089* |
| Yagisawa | | | | 6.56013 |
| Shimokubo | | | | 11.74220* |

[†] for 1977-2006; only at Aimata, precipitation data are provided as the watershed averages.

^{††} This station is operated by the Japan Meteorological Agency, and located at $36^{\circ} 24.3' \text{N}$, $139^{\circ} 3.6' \text{E}$, $H=112.1$ m, some 35 km SSE from Aimata dam. For this station, the record goes back to 1897, and over the period 1897-2006 the trend is -1.06278 , but it is not significant at the 0.05 level.

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Figure 1. Evolution of the annual lowest 7-day flows $y_{L7} = Q_{L7} / A$ (in mm d^{-1}) just upstream of the Aimata Dam reservoir since 1960. The height of this station ASL is $H = 580$ m and the upstream drainage area is $A = 110.8 \text{ km}^2$.