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Hydrological challenges in the Cauvery River basin, South India

Défis hydrologiques dans le bassin de la rivière Cauvery, Inde du Sud

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Hydrological challenges in the Cauvery[1] River basin, South India[2]

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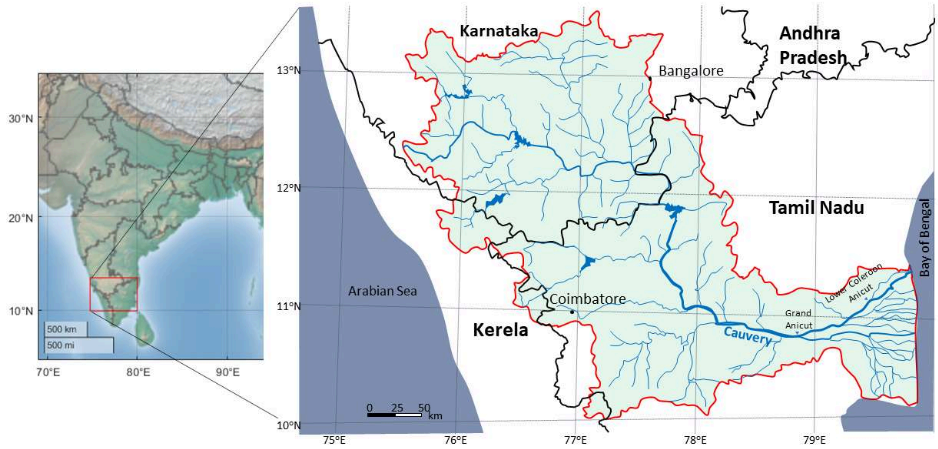
Introduction

1 The challenge of water management can be introduced by looking at the origin of the words 'river' and 'rival'. The Latin word '*rīvālis*' is defined as 'someone who uses the same stream' (Lewis and Short, 1879; Wiktionary, 2022).[3] The apparent etymological connection between 'rival' and 'river' alludes to conflicts of interest where rivers flow. Transboundary rivers may create tensions between countries and states, but at the same time it is encouraging to notice that serious conflicts are outnumbered by examples of cooperation and agreement on legislation (Wolf et al., 2003). In some cases, hydrological constrains is a challenge for optimal management of the water resources. In this article I will use the water conflict in the Cauvery catchment in Southern India (Fig.1) to illustrate some principal challenges that are emerging in many areas where water resources are endangered by over consumption. The Cauvery water conflict has been discussed for more than 200 years, but the subject is still causing tensions in Indian society (Suri, 2018). The Cauvery water conflict has been studied thoroughly by historians and social scientists (Anand, 2004; Sharma et al., 2020). The angle of approach in this article is hydrology and the concept of water balance. Rather than investigate the political, economic, and social aspects of the water conflict, the purpose of this paper is to underline the physical relation between river discharge and groundwater storage. Its goal is also to demonstrate the importance of including the physical sciences in any social science discussion of water conflicts. Given the realities of global climate change and its deleterious effects on human populations, including the inhabitants of the region under study here, the combination of political deadlock and lack of adequate social or economic responses to the climate crisis makes it all the

more necessary to include physical science modeling in social science considerations. The physical evidence is undisputable.

2 What happens with the water balance in a catchment with an original surplus of water that gradually turns into a situation of water scarcity? First, this paper provides a brief introduction to hydrology, with an emphasis on some specific challenges related to the Indian climate. Second, it briefly recapitulates the salient part of the Cauvery River dispute. Before discussing dilemmas of the water management, it is necessary to elucidate some specific challenges in the Cauvery catchment and comment briefly on different elements of its water balance.

Figure 1 : Cauvery River basin.



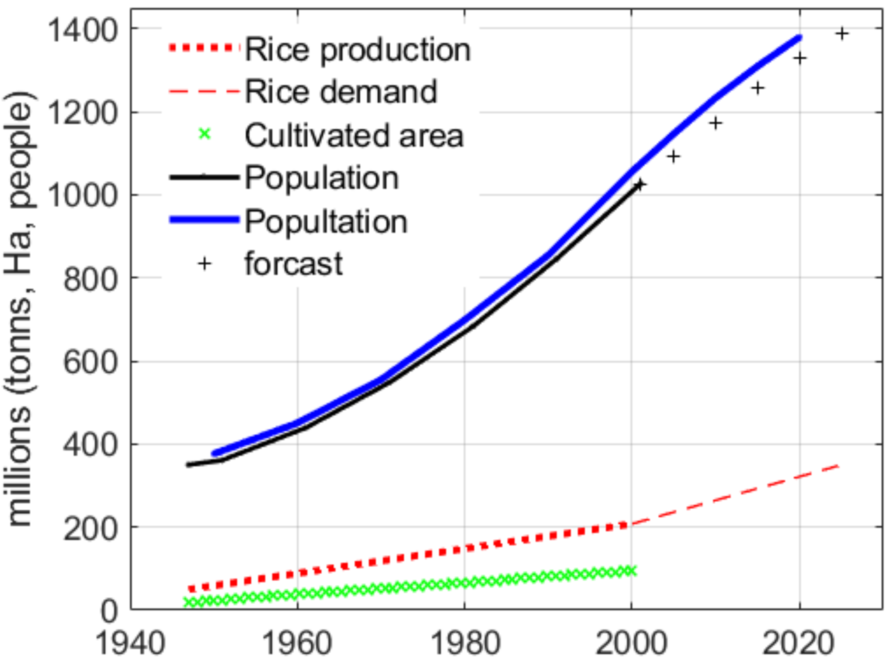
Cauvery River basin (81 155 km^2) with indications of the main rivers and artificial reservoirs (India-WRIS, 2012). The Cauvery River basin is shared by the states of Karnataka (34 273 km^2), Tamil Nadu (43 868 km^2), and Kerala (2 866 km^2), and the Union Territory Puducherry (148 km^2). Image of India (left) is made in Matlab (2022a).

Nils-Otto Kitterød.

Challenges: Food Production in India

3 India has been able to meet the food needs of its growing population through agricultural expansion and innovation (Fig.2). Especially important has been the so-called green revolution in which robust seeds with high yield, fertilizers, and pesticides were introduced along with the expansion of arable land (Fig.3).

Figure 2: Indian rice production and population data.

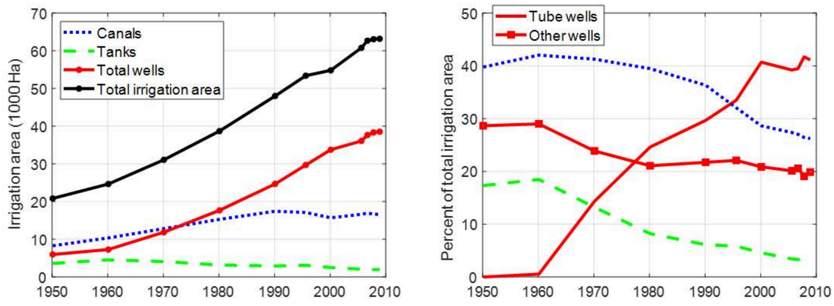


Indian rice production, estimated rice demand (million tons), cultivated area (million Ha), and populations statistics (National Water Policy, 2002). Population data from Bhat (2001, black line and crosses) and Worldometers.info (2020) blue line.

Nils-Otto Kitterød.

4 The main increase in food production took place on irrigated land. Data from most Indian states shows more than twice as high an output from irrigated land compared to non-irrigated areas (Briscoe and Malik, 2006). Before the green revolution in the 1960s, the irrigation was mainly supplied by river diversion through canals or from rain harvest in traditional micro dams (tanks), but improved drilling technology and easy access to electricity gradually increased extraction of groundwater (Briscoe and Malik, 2006). Kumar et al. (2005) estimate that groundwater covered about 45% of the total irrigation demand in India and 80% of the domestic water (Fig.3). Other studies indicate that 70% of food production comes from irrigated land in India, and 60% of total irrigation water is groundwater (Gandhi and Bhamoriya, 2011).

Figure 3: Irrigation method and irrigation areas in India.



Irrigation method and irrigation areas in India. Left: Total irrigation area in India, and irrigation area supplied by different sources: canals, tanks, groundwater wells. Right: Irrigation sources as percent of total irrigation area. Data from Gandhi and Namboodiri (2002) and Ministry of Agriculture (2010) published in Gandhi and Bhamoriya (2011).

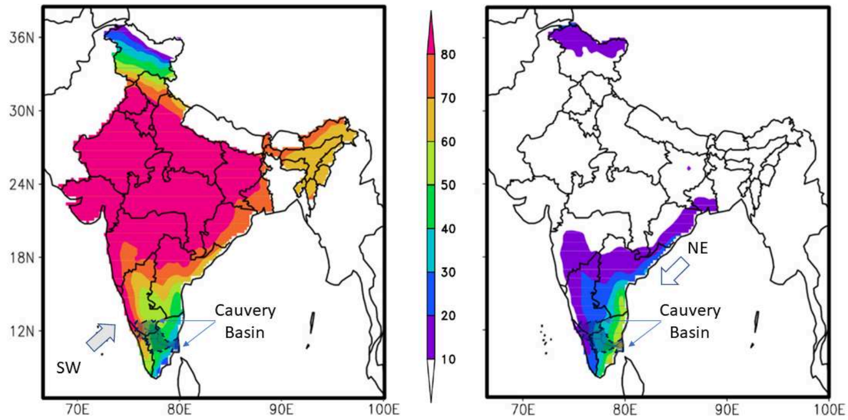
Nils-Otto Kitterød.

5 Indian agriculture depends on the Indian Summer Monsoon (ISM), which is a major component of the larger Asian Summer Monsoon (ASM) system. However, the physics of the ASM is difficult to model, and long-term forecast of precipitation is therefore a subject of substantial research (Hanf and Annamalai, 2020; Meehl et al., 2020). The ASM climate system is characterized by non-linear feedbacks between ocean temperature and atmospheric circulation. In given circumstances ISM releases tremendous amounts of energy which generate vigorous local weather conditions and affect large parts of the global climate (Annamalai et al., 2011). The circulation pattern over the Indian continent is characterized by the South-West (SW) summer monsoon, which normally comes during the period from June to September, and the less regular North-East (NE) winter monsoon, which is most active from November to December. The SW-monsoon normally provides the most precipitation over India except for the southern parts of India, which typically receives most of its precipitation from the NE-monsoon (Fig.4).

Water Balance

6 The theoretical concept of water balance is simple: the difference between in-flux and out-flux of water for a specified domain in space and time is equal to the change in water storage. If the specified domain is confined and not too large, quantification of the water balance is trivial. In an open landscape, however, quantification of the water balance is not so easy. In practice, hydrologists estimate the water balance within a catchment area. The definition of a ‘catchment or river basin[4]’ is ‘an area in the landscape in which precipitation is collected and then transferred as liquid water to a specified outflow location (e.g., streams, rivers, lakes, or coastal areas)’. In the text below I use the Cauvery River basin (Fig.1) as an example to illustrate problems related to the water balance.

Figure 4: Spatial distribution of rainfall over India.



Spatial distribution of rainfall over India in percent to the annual rainfall. The left panel illustrates the contribution from the South-West (SW) summer monsoon (June, July, August, and September). To the right is the North-East (NE) winter monsoon (October, November, and December). The Cauvery River basin (Fig.1) is indicated by stippled line. The figures show the result from the Multi-model mean from the National Aeronautics and Space Administration (NASA) Earth Exchange Global Daily Downscaled Projections (NEX-GDDP, Thrasher et al. 2012). The results are consistent to the India Meteorological Department (IMD) high-resolution daily gridded rainfall data for the period 1976–2005 (Pai et al. 2015). The left and right panel are modified version of Fig. 2 in Rao et al. (2020).

Nils-Otto Kitterød.

The water balance over a catchment area A [L^2], for a time period Δt [T], can be described in a simple equation: (1) $\Delta S/\Delta t = P - E - R + \varepsilon$,

where ΔS [L] is change in water storage, P [L/T] is precipitation, E [L/T] is evapotranspiration (i.e. evaporation and transpiration merged into one term), R [L/T] is runoff, and ε [L/T] is the uncertainty. If the size of the area A is small, and the time interval is short, the uncertainty ε, may be in the same order of magnitude as the other terms in the equation. The units (in square brackets) are length L and time T, which indicate that the members in Equation 1 are averages over the area A and the time interval Δt. Water extraction is usually included as a sink term in Equation 1, which removes the extracted water (mathematically) from the water budget equation (Equation 1). In the Cauvery River basin, most of the extracted water goes to irrigation, which is 'lost' mainly to evapotranspiration and partly to surface runoff or to groundwater recharge (Kitterød et al, 2011). Ultimately, the long-term limit for human consumption of water is the surplus of precipitation minus evapotranspiration. This surplus corresponds to the long-term average runoff R. This can easily be seen from Equation 1 because the left-hand side of the equation ΔS/Δt, approaches zero as Δt becomes larger.

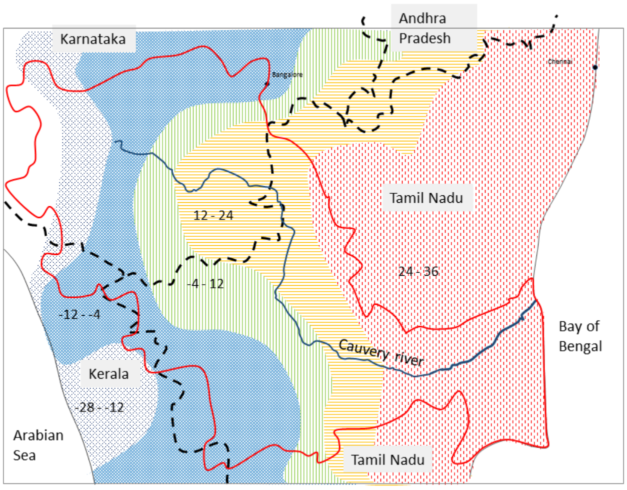
Precipitation

7 Precipitation in India depends on the dynamics of the Indian Summer Monsoon (Kumar et al., 2005; Meehl et al., 2020). The temporal and spatial variability over the Indian continent is enormous. Average precipitation in India was estimated to about

1150 mm/year (Kumar et al., 2005). In the North-eastern part of India (Meghalay) more than 1000 mm/day has been recorded, while in the Western part of the country (Jaisalmer) there may be as little as 150 mm/year of rainfall. About 20% of the Indian continent has precipitation levels of less than 750 mm/year on average, and barely 15% has precipitation levels above 1500 mm/year (Kumar et al., 2005).

8 Mutual feedbacks between global warming and the Asian Monsoon system affect precipitation amounts. Data analysis of long term (50 years) time series shows an increase in precipitation over the southern Indian peninsula, especially over Tamil Nadu during the NE winter-monsoon (Fig.5). This picture, however, is modified by a minor decrease in precipitation for the western parts of the Cauvery River basin (Annamalai et al., 2011). The regularity of the Indian Summer Monsoon depends on the coupling between ocean temperature and the atmosphere - known as the El Niño-Southern Oscillation (ENSO). Global warming and the ENSO physics is a cardinal topic in climate modelling (Meehl et al., 2020; Annamalia et al. 2011; Annamalia et al. 2007), but the consequences on the Indian Summer Monsoon is not fully understood and require more attention (Beal et al. 2020).

Figure 5 : Long-term rate of change in precipitation over Southern India.



Long-term rate of change in precipitation derived from observations in 1951-2008. The numbers indicate millimeter of change in precipitation during the North-East monsoon (Oct.-Dec.) averaged over 50 years. The dashed lines indicate state boundaries (modified from Annamalai and Nagothu, 2009 in Nagothu et al. 2011).

Nils-Otto Kitterød.

9 The global average temperature for the decade 2011-2020 has increased 1.09°C [0.95 to 1.20]°C since the period 1850-1900 (90% confidence interval given in brackets). The average temperature increase is expected to continue, but the level depends on emission of greenhouse gases (IPCC, 2021). The temperature build up is not uniformly distributed around the globe. The observed temperature increase for India for example, was estimated to 0.7°C from 1901-2018 (Krishna et al, 2020). The impacts of global warming on the local water balance, are even more difficult to predict. From a purely physical point of view an increase in temperature will amplify evaporation and air humidity. More moisture in the air will create more precipitation, but where and when

the precipitation will fall is not evident. According to IPCC (2021) the Indian Monsoon precipitation is increasing as a response to greenhouse gas warming. The improved atmospheric circulation modelling is also able to capture the observed decrease in monsoon precipitation from the 1950s to the 1980s, which was due to the emissions of anthropogenic aerosols in the atmosphere. It should be noticed that IPCC (2021) report these results with medium confidence, which indicate that the modelling results are affected by uncertainties.

Evapotranspiration

10 The amount of water flux from the surface of the Earth into the atmosphere is the source of all precipitation. The transition from liquid water to water vapor is equivalent to an energy flux, which consists of two parts: evaporation from open water and transpiration from plant tissues. These two processes are governed by the same physics, and they are therefore usually described in one term: evapotranspiration. Evapotranspiration depends on the temperature in the water, air humidity above the surface, soil moisture content, and vegetation on the land surface. The physics involved are energy and turbulence. Turbulence in the atmosphere is caused by wind speed, and because wind fluctuates rapidly, evaporation is difficult to measure directly and quantification over large areas relies mainly on computer modelling. Thus, the main uncertainties in Equation 1 are usually related to evapotranspiration. Impact studies of global warming on local evapotranspiration require coupling of large-scale ocean-atmospheric circulation models with local land surface processes. Using such models (usually called Earth System Modelling), researchers can include impacts on chemistry, biology, and also changes in land use due to human activity (Döscher et al. 2017). Human activity systematically modifies the natural water balance, for example through the construction of artificial reservoirs and large-scale irrigation systems. (Haddeland et al. 2006). Earth System Modelling indicates an increase of about 10% to 15% of evapotranspiration due to irrigation practices in the Indian subcontinent (de Rosnay et al., 2003, Haddeland et al. 2014). Modeling results for the Cauvery River basin has been difficult to assess, but similar figures are probably relevant for the Cauvery River basin. An increase of evapotranspiration means reduction in runoff (Equation 1).

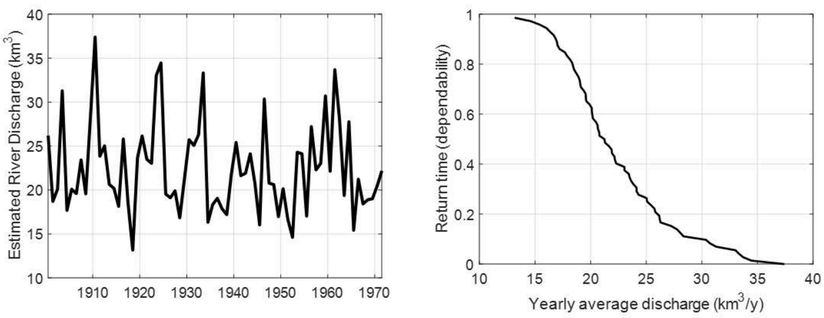
Runoff and Groundwater Recharge

11 Runoff R, takes place as a continuous process in time and space. Most runoff goes normally through the subsurface and end up as discharge Q, in streams and rivers. Discharge Q, is therefore equivalent to runoff R [L/T], integrated over the catchment area A [L^2]. Here, [L] is a length unit and [T] is a time unit, thus Q is given as volume pr. time [L^3/T]. Because most of the runoff goes through the subsurface, the major fraction of runoff is identical to groundwater recharge. In periods with intensive precipitation, water may flow on the surface directly to the water course, but even during such events, tracer tests indicate that a major fraction of the river water has travelled through the ground (e.g. Dingman, 2015, p477ff). Because discharge Q, integrates all hydrological processes in the upstream catchment area A, assessments of water resources typically start with measurements of water discharge and delineation of the catchment. The Cauvery River basin begins in the Western Ghats Mountain range in the

western part of Karnataka state and ends at the Tamil Nadu coastline in the Bay of Bengal. The Cauvery River basin (81 155 km^2) is shared by several states: Karnataka (42.2%), Tamil Nadu (54.1%), Kerala (3.5%), and the Union Territory Puducherry (0.2%). Karnataka and Kerala are upstream states while Tamil Nadu is the downstream state, which also includes the territory of Puducherry - the Karaikal district, on the Cauvery delta (Fig.1).

12 Accumulated yearly discharge (Q) measured at the Lower Coleroon Anicut (also called Anaikkarai) from 1900 to 1971 indicates a total volume of water between 13 km^3 and 37.4 km^3 per year (Fig.6). These numbers give an average runoff $R=Q/A$, for the total catchment area A, between 162 mm/year and 461 mm/year. Based on the time series in Fig.6, a simple duration curve can be derived, which shows that for every second year the discharge at Lower Coleroon Anicut was less than 21.23 km^3/year (Fig.6). According to Anand (2004), the upstream states Kerala and Karnataka have average runoffs between 1117 mm/year and 352 mm/year, while the catchment area in Tamil Nadu average runoff s was estimated to 163 mm/year, which correspond well to the observations given in Fig.6. Such average numbers, however, are not very helpful when it comes to agreements among population groups on how to share water resources because an average number does not consider either natural variability, or the uncertainties in the measurements. The expected change in runoff due to global warming is unclear. Regardless of the likely effects of global warming, the demand for water is expected to increase due to growth in population and economy. An increasing demand for water combined with highly variable access makes the question about water storage to a delicate political subject.

Figure 6. Discharge at the Lower Coleroon Anicut.



Left panel: Yearly average discharge measurements at the Lower Coleroon Anicut (Fig. 1) for the period 1900 to 1971. Right panel: Discharge return period at Lower Coreroon Anicut based on discharge measurements period 1900 to 1971 (left panel). Geographical coordinates of gauge station: 11° 8' 20" N, 79° 27' 6" E. Data source: CFFC, 2007b, pp. 76-77).

Nils-Otto Kitterød.

Water Storage

13 Water storage (symbolized with ΔS in Equation 1) comprises all types of water that has a long residence time in the catchment, compared to runoff, precipitation, and evapotranspiration. Groundwater constitutes the most important natural storage volume. In Tamil Nadu, which is in the lower part of the Cauvery River basin, the subsurface naturally stores large volumes of water. In these regions, sedimentary deposits with high porosity and good permeability create large storage volumes and good water yield. Groundwater in fractured rocks is also exploited for irrigation and domestic water supply. Water from deep boreholes, however, can have high concentrations of dissolved minerals and render it less suitable for irrigation. Water from deep boreholes can also have too high temperature for rice paddy crop cultivation (Dhinagaran,2008).

14 Water storage can be increased by the construction of artificial reservoirs. Total dam capacity in India increased from 77.5 km^3 in 1962 to 247.5 km^3 in 2018 (FAO, 2022). This provides a dam capacity of less than 200 m^3 per capita in India (FAO, 2022). Within the Cauvery River basin, the state of Karnataka has artificial storage capacity of approx. 3.2 km^3 (CFFC, 2007a), while the state of Tamil Nadu had a total storage capacity of 3.7 km^3 (CFFC, 2007b; Geethalakshmi et al. 2011). India Water Resources Information System reports 8.87 km^3 large dam storage capacity in the Cauvery River basin (India WRIS, 2012). These storage volumes can only cover a minor fraction of the demand for water. Groundwater is used to compensate for the water deficit.

Water Consumption

15 India's irrigation water requirement was estimated to 370 km^3/year in 2018 (FAO, 2022). The agricultural demand for water was about 90% of the total water withdrawal and 36% of total renewable water resources. Exact figures for the Cauvery River basin were not easily accessible, but relative to renewable water resources, the agricultural demand for water in the Cauvery River basin is likely in the same order of magnitude or even higher than for other parts of India.

16 According to the national Indian guidelines for water use, domestic water supply has the highest priority. Bangalore receives its water supply from the Cauvery River basin, and the principle of priority for domestic water supply is therefore an argument for Karnataka to increase its share of water. Farmers within Karnataka also receive surface water from the dams. The net result is that less and less water is being released from Karnataka to Tamil Nadu. In years with a surplus of precipitation, Karnataka can release water according to the agreements between the two states, but in years of water deficit, the amount of water that Karnataka is obliged to release causes social tensions (Anand, 2004). This is the kernel of the Cauvery River basin water dispute. The Cauvery Fact Finding Committee (CFFC, 2007b) states that utilization of surface water in the Cauvery catchment has increased from about 14.2 km^3/year (502 TMCft per year)[5] in 1901 to 21.2 km^3/year (750 TMCft per year) in 1971. With an increase in food production, the actual water consumption today is higher. The difference between groundwater recharge and extraction of groundwater indicates an average depletion of water resources between 0.4 and 1.6 km^3/year (Tab.1).

Table 1. Estimates of the Water Balance for the Cauvery River basin.

Variable	Status	Source
Trend in average precipitation	0-30 mm/50 years for NE monsoon	Annamalai & Nagothu (2009)
Average temperature	Increasing trend	Annamalai & Nagothu (2009)
Average runoff 50% dependable runoff 75% dependable runoff 90% dependable runoff	21.4 km^3/year 21 km^3/year 19 km^3/year 17.6 km^3/year	MoWR (2009) CFFC (2007b) CFFC (2007b) CFFC (2007b)
Surface water consumption[a]	21 km^3/year	CFFC (2007b)
Groundwater recharge	1 – 7,6 km^3/year 19.81[b] km^3/year	Wada et al. (2010), and Chatterjee & Purohit (2009) Chinnasamy & Agoramoorthy (2015)
Groundwater extraction	2.3 - 4,6 km^3/year 3 - 6[c] km^3/year 0.6 – 3 km^3/year 21.4[d] km^3/year	CPCB (1995) Chatterjee & Purohit, 2009 Wada et al. (2010) Chinnasamy & Agoramoorthy (2015)
Groundwater depletion[e]	0.4 -1,6 km^3/year 1.6[f] km^3/year	Wada et al. (2010) Chinnasamy & Agoramoorthy (2015)

a. Consumption figures from 1901-1971 (CFFC, 2007b).
b. Estimate for entire Tamil Nadu.
c. Based on estimated figure for Tamil Nadu and corrected for max recycling factor of 0.45 (Chatterjee & Purohit, 2009).
d. Estimate for entire Tamil Nadu.
e. Groundwater depletion is equal to groundwater recharge minus groundwater extraction.
f. Estimate for entire Tamil Nadu.

The Cauvery Water Dispute

17 The Cauvery water dispute is quite intricate, and a thorough review of the Cauvery water dispute is beyond the scope of this article. Readers can find more information in Anand (2004), and reports from the Cauvery Fact Finding Committee (CFFC, 2007ab). In the following I highlight some key observations, which gives the hydrological framework for the water authorities when they make their management decisions. The background for the conflict lies in the agreements written in 1892 and 1924 between the former states of Mysore and Madras. Mysore later became a part of Karnataka and part of Madras belongs today to Tamil Nadu.

18 Several irrigation projects were developed in Mysore and Madras in the period between 1892 and 1924. In 1892, Mysore was allowed to develop irrigation on the condition that Madras was given assurances of water security (Anand, 2004). In practice, no irrigation project could be implemented in Mysore without clearance from the Madras state. Between 1900 and 1910 the first phase of the Krishna Raja Sugar (KRS) dam in Mysore was accepted, but objections against the second phase were raised because Madras demanded guarantees that the project would not affect inflow to the Mettur dam. In 1924, new agreements were signed, and Mysore was permitted to develop the second

phase of KRS with a storage volume of 1.2 km^3 (41 TMCft). In return Mysore had to limit its total irrigation area to about one third of the irrigation area that was initially allowed in the Madras state. After fifty years the agreement was intended to be reviewed, but the details or structure of the revision were not specified.

19 The 1924 agreements might be described as inventive for their time, but they had some weak points: First, the management structures that were implemented as part of the agreement did not have enough flexibility to anticipate new demands. Such demands were emerging in the up-stream areas as well as in down-stream areas as a function of population growth and economic development. Second, the agreements had weak formulations on allocation of water in years of water scarcity. Instead of focusing on the benefits of water, the agreement had a deterministic bias on water quantities and neglected the challenge of natural variability. Finally, the agreement had no clear procedures to solve conflicts of interests.

20 Discussions on the agreement started in the 1960s and 1970s and culminated in 1981. At that time, Karnataka claimed 13.2 km^3 (465 TMCft), Kerala 2.8 km^3 (100 TMCft), and Puducherry 0.3 km^3 (10 TMCft), together 16.2 km^3 (575 TMCft) per year. Tamil Nadu on the other hand, claimed the right to water according to the 1892 and 1924 agreements. At that time, the estimated total utilization of Cauvery water was 21.2 km^3 (748 TMCft), Tamil Nadu and Puducherry: 16,0 km^3 (566 TMCft); Karnataka 5.0 km^3 (177 TMCft); and Kerala 0.1 km^3 (5 TMCft). In 1991, Karnataka was directed by an interim tribunal to release 5.8 km^3 (205 TMCft) to Tamil Nadu with specified quantities for each month (CFFC, 2007a, p71-72). Karnataka was not happy with the decision and appealed to the Supreme Court of India, but Karnataka's objections were not supported by the central government (Anand, 2004; Wikipedia, 2022). Up to 25 people were killed in the following violent protests (Anand, 2004). The decision has been a subject of debate since that time, and the dispute has ended up in court several times. In a tribunal in 2007, the basic principles from the interim awarded in 1991 were confirmed, but the amount of the water release from Karnataka was reduced to 5.4 km^3 (192 TMCft). In 2018, the Supreme Court decided that Karnataka could decrease the release to Tamil Nadu with 0.4 km^3 (14.75 TMCft). Thus, this verdict further reduced the imposed water release to 5.0 km^3 (177.25 TMCft, India.com, 2018). The decision was based on the principle that domestic water supply to Bangalore had the top priority, and that Tamil Nadu had unexploited groundwater reserves (SANDRP, 2018). Karnataka's and Tamil Nadu's main arguments against the tribunal's decision are summarized below (Anand, 2004).

21 The main arguments of Karnataka:

- The agreement in 1924 was imposed on Mysore according to principles held under British rule. The downstream state was given disproportionate large amounts of water resources due to colonial priorities, and the allocation of water should be revised after 50 years in accordance with the agreement.
- Farmers up-stream have the same right to irrigation water as those down-stream.
- Karnataka receives most of its water from the South-West (SW) monsoon (June-September). In Tamil Nadu most of the rain is received from the North- East monsoon (November-December), but Tamil Nadu benefits also from the SW monsoon by the discharge in the Cauvery River. The agreement does not consider the unequal distribution of precipitation between the two states.

- In years of water distress, the down-stream area should not have an unequal right to water compared to the up-stream areas. Release of water to down-stream farmers is perceived as unfair when there is no water for irrigation to up-stream farmers.
- The allocation of water should consider the spatial differences in runoff and the fraction of areas that are prone to droughts.

22 The arguments of Tami Nadu:

- The long history of rice production in the Cauvery delta zone cannot be ignored. Paddy farming depends on Cauvery discharge from the SW summer monsoon.
- Farming after the agreements in 1892 and 1924 has developed mainly due to canal irrigation. Today, numerous farmers depend on diversion of water from the Cauvery River. Reduction of irrigation water has detrimental impact on the population in the Cauvery delta zone.
- Natural variability in the Indian Summer Monsoon cannot be used as an argument to deny release of water from Karnataka to Tamil Nadu. Karnataka is welcome to utilize the SW summer monsoon for irrigation as long as the legal amount of water is released down-stream to the Mettur dam.
- The water in an interstate river is common property. The up-stream state has no right to retain water without taking down-stream interests into account.

Water Management Challenges

23 The summary above indicates the historical context of the conflict. From this perspective, the Cauvery water dispute is unique. Anand (2004) analyzed the conflict from a political science point of view and underlined some general aspects that might be valid for other water disputes. The Cauvery water crisis should also be discussed in terms of hydrology. I want to highlight in particular two hydrological challenges which need more attention. The first challenge is related to groundwater pumping and water balance. The second challenge is relevant for the augmentation of artificial water storage.

24 So far, the increasing demand for irrigation water has been met by groundwater extraction. A premise for the Supreme Court verdict in 2018 was that Tamil Nadu had a groundwater reserve which was not accounted for in previous decisions (*The News Minute*, 2018). A review of the water balance in the Cauvery River basin indicates however, that the extraction of groundwater exceeds the groundwater recharge (Tab. 1). Time series derived from satellite images confirms the trend in groundwater depletion from 2002 until the end of the study in 2015 (Chinnasamy and Agoamoorthy, 2015).

25 Extraction of groundwater has obvious benefits for its users: Consumers control delivery themselves, simple technology is involved, no administration is required, and the timing of irrigation is user defined. The current consumption of groundwater, however, is a serious challenge: Groundwater extraction meets an acute shortage of irrigation water, but the current practice is not sustainable. Depletion of groundwater is the consequence. This is observed in a falling groundwater table in open aquifers and a reduced groundwater head in confined aquifers. Shallow wells go dry, and tube wells need to be drilled deeper. A lowering of the groundwater table means higher pumping costs and hazard for water quality. A permanent decline of the groundwater table increases residence time of water in the subsurface. Long residence time increases concentration of dissolved minerals in the groundwater due to chemical weathering.

High concentrations of dissolved minerals can make the water unsuitable for irrigation in extreme cases (Lalitha et al., 2021). A lower groundwater table also implies less base flow to streams and rivers, which means that perennial streams and rivers might run dry during periods of drought. This could lead to devastating conditions downstream where the population depends on perennial water discharge.

26 In theory, groundwater extraction cannot exceed groundwater recharge on a permanent basis simply because the storage volume cannot be less than zero. Thus, groundwater depletion must be controlled because of negative environmental and economic consequences. To avoid groundwater depletion, it is necessary to carefully balance use of groundwater wells and monitor groundwater levels. Financial instruments (*viz* taxing of groundwater pumping, pricing of water use) might be necessary to control consumption. Such measures, however, must be fair and transparent to avoid abuse.

27 The second challenge is linked to the construction of dams. Most developing countries control their water resources through the construction of artificial reservoirs. Dams have obvious advantages, especially for people living in the vicinity of the reservoir. Local people have easy access to water supply and hydropower. Water storage in dams, however, has impacts on water balance downstream. Evaporation from open water is substantial. An artificial reservoir means that the surface area of open water is large. For example, evaporation from the Aswan dam in Egypt is estimated to 2.3 - 2.5 m/year (Hassan et al., 2018). If the same magnitude of evaporation is valid for the Cauvery River basin, a surface reservoir of 40 km^2 would lose 0.1 km^3/year (3.6 MTCft per year) due to evaporation.

28 The purpose of a reservoir is to increase irrigation, which means more evapotranspiration and less release of water for canal irrigation downstream. Hydropower is usually one of the intentions of dam constructions, but an indirect consequence is increased use of groundwater because farmers acquire access to electricity for pumping. The net effect is an augmentation of groundwater extraction. If the drilling of wells and the consumption of electricity are subsidized to mitigate acute water shortages, this may help for a limited period, but increase permanent problems with over consumption (Briscoe and Malik, 2006).

29 Another hydrological challenge is transport of sediment in rivers and silting of dams. In delta areas there is a dynamic balance between sedimentation from the river and erosion by the sea. A reduction in sediment transport has an impact on the elevation of river channels and the delta plains. The net impact of less sediment transport is seawater intrusion in the delta. This is reported as a serious problem in the coastal area of Tamil Nadu and the Cauvery delta coastline (Prusty and Farooq, 2020).

Summary

30 In this article, the water balance equation is used to illustrate hydrological challenges in the Cauvery River basin. The Indian Summer Monsoon determines the water balance in the region, which exposes the Cauvery River basin both to periods of heavy rain and frequent floods and to long periods of water scarcity and drought. Construction of large water reservoirs mitigates flood risks and provides water supply for irrigation, domestic consumption, and industry. Interventions in the water balance such as dam construction and groundwater extraction have been successful in terms of food

production and economic development, but water consumption is approaching its upper limits for sustainable use. The upper limit for water consumption in a river basin is given by the water balance (Equation 1). Short term water scarcity can be controlled by groundwater pumping, but permanent increase of groundwater extraction cannot continue without serious environmental and social impacts.

31 The natural variability of the Indian Summer Monsoon defines the framework for water resources management in the Cauvery River basin. This variability poses a permanent challenge for the population, but the study of past events has proven that hazards from flooding and drought can be minimized and controlled by economic and technical development. Focused efforts on monitoring and active implementation of legislation are necessary to avoid mismanagement of water resources which turn fertile soil to waste land.

32 The impacts of global warming on the local water balance in the Cauvery River basin are not clear. IPCC (2021) reports an expected increase in Monsoon precipitation for South India, which is supported by observations of precipitation from 1951-2008 (Fig.5). At the same time evapotranspiration is expected to increase due to more irrigation. The net-effect on renewable water resources is therefore uncertain. Irrespective of climate change, the current stress on water resources will continue to increase and careful regulation (as prizing of water use) is necessary to avoid a detrimental impact on the rural population. The Cauvery water dispute illustrates the long-term effects of neglecting the water balance. In addition, today's water authorities have limited room for mitigation of the conflict between the states involved (Anand, 2004).

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NOTES

1. 'Kaveri' is an alternative spelling for 'Cauvery'

2. Thanks to colleagues and friends for input and comments: Nagothu for inviting me to join the ClimaRice project, Annamalai for sharing research on the Indian Summer Monsoon, Geethalakshmi for hosting me in Coimbatore and introducing me to farmers and agriculture in the Cauvery River basin, Carpenter and Solerød for reading a manuscript draft, and Natalie and Perrine Fernandez for helping me with the initial French résumé. Finally, a big thanks to Marie Bolton and Patrick Fournier for taking the initiative to organize this project and all their support during the writing.

3. This article uses parenthetical citations in conformity to standard use in the field of hydrology.

4. In the literature catchment, watershed, drainage basin or river basin is used as synonyms (Dingman, 2015). In this context, I use the term 'river basin' to underline a large catchment area with a nested structure of sub-catchments.

5. TMCft (thousand million cubic feet), 1 km^3 = 35.32 TMCft. CFFC (2007ab) gives volumes in TMCft and these numbers are therefore given in parenthesis.

ABSTRACTS

Abstract: Hydrology in the Cauvery River basin reflects the physics of the Indian Summer Monsoon. Optimal management of the water resources is a permanent challenge due to the natural variability in the monsoon system. Global warming affects precipitation and evapotranspiration, but the coupling to the variability of the climate system is still a matter of debate. These natural challenges have been augmented by an increasing demand for water due to a growing population. Upstream and downstream conflicts of interest add to these challenges. In the Cauvery River basin, these conflicts of interests were expressed in the dispute between Karnataka - the upstream state, and Tamil Nadu - the downstream state. A brief review of these challenges is given in this article with emphasis on the principal challenge in hydrology, namely quantification and management of the water balance. Essentially, runoff defines the upper limit for human water consumption. In periods with water deficit, groundwater storage serves as a buffer. Overexploitation of groundwater results in a declining water table. A permanent lowering of the groundwater level has unfavorable side effects: shallow wells dry out, and more power is required to pump water from deeper boreholes. More serious impacts are degradation of groundwater quality and reduced baseflow to streams and rivers. To illustrate some principal dilemmas regarding management of water resources, a summary is given of the main arguments in the water dispute between the states of Karnataka and Tamil Nadu.

Résumé : L'hydrologie du bassin de Cauvery reflète la physique de la mousson d'été indienne. La gestion optimale des ressources en eau est un défi permanent en raison de la variabilité naturelle du système de mousson. Le réchauffement climatique affecte les précipitations et l'évapotranspiration, mais le lien avec la variabilité du système climatique est encore un sujet de débat. Ces défis naturels ont été accrus par une demande croissante en eau due à l'augmentation de la population. Les conflits d'intérêts en amont et en aval viennent s'ajouter à ces défis. Dans le bassin de Cauvery, ces conflits d'intérêts se sont exprimés dans le différend entre le Karnataka – l'État en amont, et le Tamil Nadu – l'État en aval. Une brève revue de ces défis est donnée dans cet article en mettant l'accent sur le principal en hydrologie, à savoir la quantification et la gestion du bilan hydrique. Ce qu'il faut retenir est que la somme des écoulements du bassin versant fixe la limite supérieure de la consommation d'eau. En cas de nécessité, le stockage de l'eau pallie le déficit hydrique jusqu'à ce que les réserves soient épuisées. Dans les zones où les eaux souterraines sont utilisées, la surexploitation entraîne une baisse de la nappe phréatique. Un rabattement permanent du niveau des nappes phréatiques a des effets secondaires défavorables : les puits peu profonds s'assèchent et il faut plus d'énergie pour pomper l'eau des puits plus profonds. Les impacts les plus graves sont la dégradation de la qualité des eaux souterraines et la réduction du débit de base des ruisseaux et des rivières. Pour illustrer quelques principaux dilemmes concernant la gestion des ressources en eau, un résumé est donné des principaux arguments dans le différend sur l'eau entre les États du Karnataka et du Tamil Nadu.

INDEX

Keywords: Indian Summer Monsoon, global warming, hydrology, groundwater, rice production, water conflicts, Cauvery River basin, South India, 20th century
Mots-clés: mousson d'été indienne, réchauffement climatique, hydrologie, eaux souterraines, production de riz, conflits liés à l'eau
Geographical index: Bassin de la rivière Cauvery, Inde du Sud
Chronological index: XXe siècle

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