The Cauvery river basin in Southern India: major challenges and possible solutions in the 21st century

D. Vanham, R. Weingartner and W. Rauch

ABSTRACT

India is facing major challenges in its water resources management (WRM) sector. Water shortages are attributed to issues such as an explosion in population, rapid urbanization and industrialization, environmental degradation and inefficient water use, all aggravated by changing climate and its impacts on demand, supply and water quality. This paper focuses on the contemporary and future situation in the Cauvery river basin in Southern India, shared by different states, predominantly Karnataka and Tamil Nadu. As water issues largely fall under the authority of the states, inter-state water disputes have a long tradition in the Cauvery river basin. Future changes in precipitation during the two monsoon seasons will only increase these tensions. Both states depend on the arrival of these monsoon rains to water their crops and to replenish the groundwater. The paper identifies the major challenges and general possible solutions for sustainable WRM within the river basin. It synthesises the relevant literature, describes practices that should be addressed in the scope of integrated WRM – including water availability increase and demand management – and stresses the need for further quantitative analyses.

Key words | Asia, Cauvery, India, integrated water management, IWRM, river basin management

D. Vanham (corresponding author)
W. Rauch
Unit of Environmental Engineering, Institute of Infrastructure,
University of Innsbruck,
Technikerstrasse 13,
6020 Innsbruck,
Austria
E-mail: *davy.vanham@yahoo.de*

R. Weingartner
Hydrology Group, Institute of Geography,
University of Berne,
Hallerstrasse 12,
3012 Berne,
Switzerland

INTRODUCTION

By 2050, most of the Indian subcontinent will experience (severe) blue water stress (Alcamo *et al.* 2007). In India average per capita water availability is expected to fall from 1,902 m^3 in 2001 to 1,401 m^3 in 2025 and 1,191 m^3 in 2050 (Kumar *et al.* 2005). The total population increased from 361 million in 1951 to 1027 million in 2001, and is projected to increase to between 1,346 (low growth) and 1,581 (high growth) million by 2050. This massive population growth is expected to flatten as a country average towards 2050. The current total annual water requirement of ~700 km^3 (80% for irrigation) will increase substantially in future. The relative proportion for irrigation will drop, whereas the proportions for domestic and industrial use will increase. Spatial inequality in the country is large. Per capita water availability is for example much higher in the wet Brahmaputra basin as in the drier Cauvery basin. As water resources development is a state responsibility, all states are required to develop their water policy within the framework of the national water policy adopted in 1987. Water allocation priority has been given to (1) drinking water, (2) irrigation, (3) hydropower, (4) ecology, (5) industry, (6) navigation and other uses.

doi: 10.2166/wst.2011.554

THE CAUVERY RIVER BASIN: MAJOR CHALLENGES

Water availability

The Cauvery river basin (Figure 1) is primarily located in the states of Karnataka and Tamil Nadu. Also Kerala and the Union Territory of Pondicherry (Puducherry) share a part of the basin. The western part is characterized by the Western Ghats mountain range, with elevations reaching over 2,000 m a.s.l. The Cauvery flows into the Bay of Bengal in an extensive delta system.

Most of the rainfall in southern India takes place under the influence of the southwest monsoon between June and September, except on the eastern coast in Tamil Nadu where it occurs under the influence of the northeast monsoon during October to December (Webster *et al.* 1998;

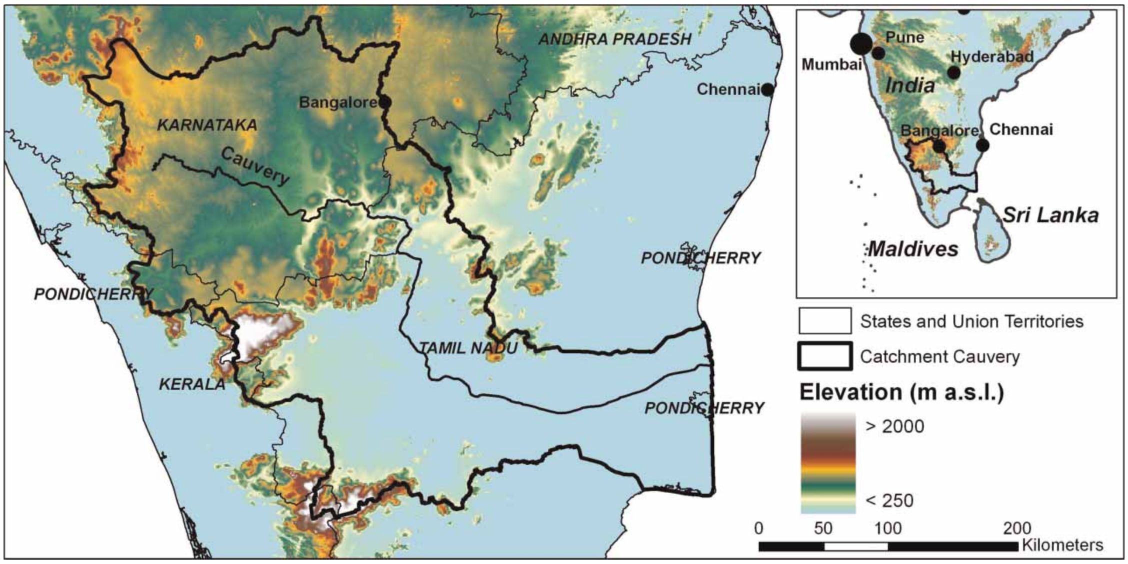

Figure 1 | Elevation range (m a.s.l.) within the Cauvery river basin.

Figure 2). The average annual precipitation reaches up to 5,000 mm in the western part of the basin whereas the amounts in the eastern part are much lower. The mean annual precipitation in the basin is about 900 mm (80 km^3 for an area of 89,500 km^2). Especially the downstream part of the basin (Tamil Nadu) is therefore very dependent on the rainfall in the upstream mountainous part, as also indicated by Viviroli & Weingartner (2004).

Due to high average temperatures the potential evapotranspiration (PET), calculated as ETo after the FAO Penman–Monteith equation (Allen *et al.* 1998), is high within the basin (Figure 3). The ratio between PET and annual average precipitation (P) is defined by UNEP (1992) as an aridity index (AI = PET/P). Large basin fractions of the semi-arid regime are found within the states of Tamil Nadu (72%) and Karnataka (74%), whereas the parts in Kerala are generally humid.

The basin annual average flow (50% dependability or normal year) is 21.36 km^3 (239 mm for 89,500 km^2), of which the NCIWRD defines 19 km^3 (212 mm) as utilizable flow (Kumar *et al.* 2005). According to Chaturvedi (2001) the utilizable flow is 21.36 km^3. The amount of total replenishable groundwater resources is estimated at 12.30 km^3 (137 mm). The sum of average annual utilizable surface flow and groundwater is thus estimated at 31.3 km^3 (349 mm) per year (according to NCIWRD), about 40% of average

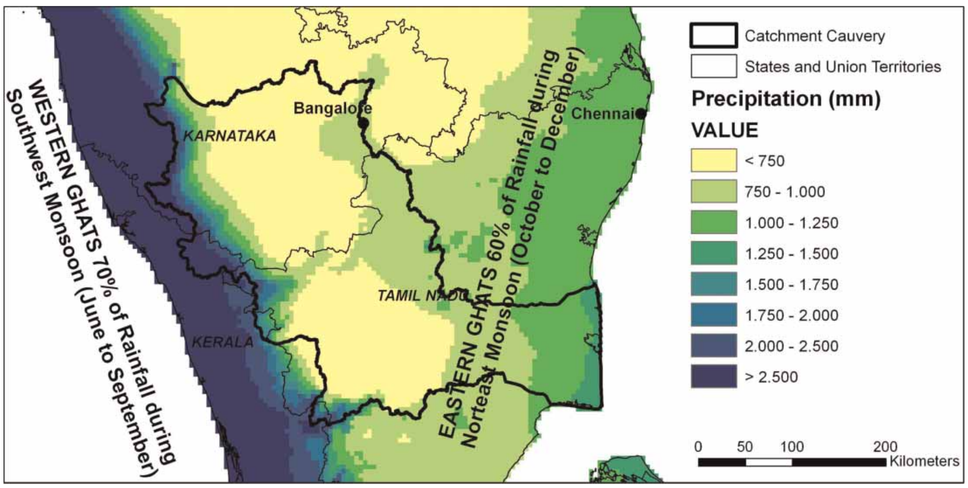

Figure 2 | Average annual precipitation (mm) for the period 1950–2000, according to Hijmans *et al.* (2005).

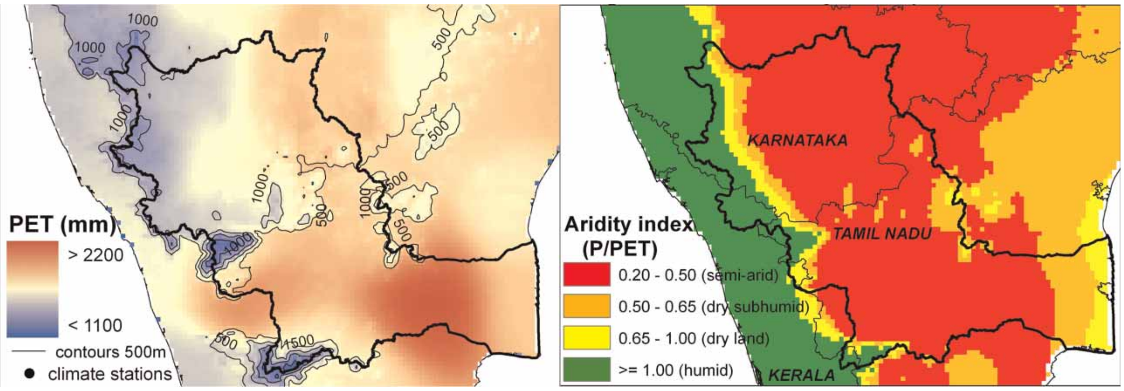

Figure 3 | Left: Average annual PET (interpolated surface from FAOClim-Database) and Right: aridity index (PET/P) in the Cauvery river basin for the existing situation.

annual precipitation. These values represent long time average values, whereas water availability during a dry year is much lower.

Changes to the annual monsoon are expected to result in severe droughts and intense flooding in parts of India. Monsoonal areas will be affected by more intense rain events over shorter rainy seasons, exacerbating flooding and erosion in catchments, as well as a higher proportion of runoff and a reduction in the proportion of groundwater recharge (Kundzewitz *et al*. 2007). This leads to less water availability when not sufficient (man-made) storage is available. Apart from the change in precipitation intensity, also a change in total precipitation amounts is expected due to climate change. Climate projections predict an increase in summer (southwest) and winter monsoon precipitation in the basin (Kumar *et al*. 2006a). Gosain *et al*. (2006) indicate for the Cauvery basin a precipitation increase, but a reduction in average normal runoff with 2% by 2050 due to higher evapotranspiration (at higher temperatures). Water availability is thus expected to decrease. Also (Alcamo *et al*. 2007) predict for the basin a reduction in water availability for 2050 (A2 scenario).

Water demand and water stress

According to National Water Policy, the first water allocation priority should be drinking water. In 2005 the average population density in the basin was 412 inhabitants per km^2 (Figure 4). This equals a population of 36.9 million (Table 1), of which 61% (density 451) is located in Tamil Nadu and 36% (density 361) in Karnataka. For an average annual total water availability of 31.3 km^3, the annual per capita water availability decreased from 1,057 m^3 in 1991 to 848 m^3 in 2005. Demographic trends at the state level (Figure 5) suggest a further population increase in the basin during the next decades. However, the population of the economically relative prosperous states of Karnataka, Tamil Nadu and Kerala (where the education degree is

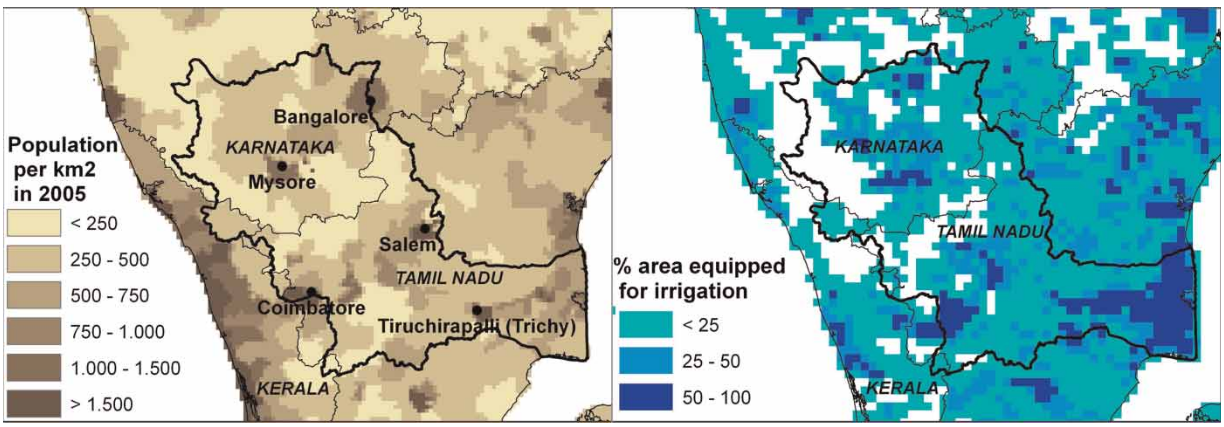

Figure 4 | Left: Population density in persons per km^2 (CIESIN-database) and right: percentage area equipped for irrigation (FAO-database, according to Siebert *et al*. (2005)) in the Cauvery basin for the existing situation.

Table 1 | Domestic and industrial water requirement in km^3 for 2011 (CWDT 2007a)

Population (million)		Domestic water demand	Industrial water demand
29.6 (in 1991)	36.9 (in 2005)	1.27	0.73

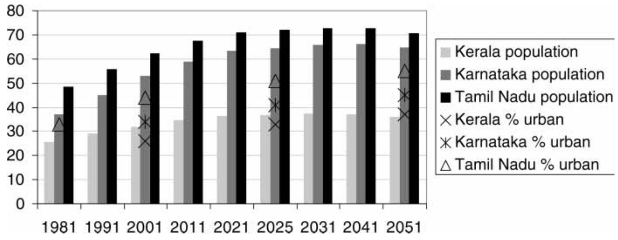

Figure 5 | Decennial total population projection (numbers in million) and percentage of urban population on the state level for the period 1981–2051. *Data sources*: Mahmood & Kundu (2008) and IWMI.

amongst the highest in India) will have a declining trend by 2050, as fertility rates drop to 1.6 between 2011 and 2021. Both the increase in total population and in percentage of urban population will lead to higher water demands for domestic purposes. A simple projection based on state values for the basin sets the population at 42 million in 2025 and 41 million in 2050. Not taking into account changes in total average water availability due to climate change, this results in annual per capita water availability of 745 m^3 in 2025 and 763 m^3 in 2050. During dry years this annual per capita water availability will be even less.

Within the report of the Cauvery Water Disputes Tribunal (CWDT 2007a), the projected domestic water requirement in the basin for 2011 is calculated (Table 1). Per capita water demand per day (lpcd) is assumed higher for urban population (range: 100–135 lpcd) as for rural population (70 lpcd). The total domestic water requirement of 1.27 km^3 represents 4% of average annual utilizable water (31.3 km^3). The total industrial water requirement of 0.73 km^3 represents 2%.

Irrigation is by far the most important water demand stakeholder in the basin. India's economy is traditionally driven by agriculture, which provides the livelihood for a large part of the population. Large areas equipped with irrigation infrastructure (17,288 km^2) are both located in Karnataka and Tamil Nadu (Figure 4). Crop water demands are high, as large areas of the basin are semi-arid (Figure 3). Almost the entire cultivation in the basin within Tamil Nadu is based on paddy crops, representing 40% of the state's rice production. The largest scheme – dating back to ancient times – is located in the Cauvery delta and serves as a food staple for Tamil Nadu. At the end of the nineteenth century, the water flowing from the river Cauvery and its tributaries were sufficient to irrigate the lands under cultivation (CWDT 2007b). The British rulers expanded the existing delta irrigation network substantially. Due to the construction of large reservoirs, regulated irrigation supply became available for the delta and farmers gradually replaced single rice crops with a double crop system. Karnataka has started to expand irrigated agriculture only in the last few decades.

Water utilization for irrigation in 2000 accounted for 60% of utilizable resources for a normal year (Table 2). Dry years pose a major threat for irrigation demands, especially as these demands increase with higher temperatures. Water demands in Tamil Nadu are the largest, but Karnataka is investing in more future irrigation infrastructure. This will put an extra burden on interstate conflicts. Also global warming will further intensify the situation, as irrigation requirements will grow with increasing temperatures (Döll 2002). Requirements for energy (and hydropower) will increase. Environmental flows in the basin are a necessity, not only for ecological reasons. An overview of environmental flows – the flow regime needed to maintain environmental functions in a river ecosystem – in the basin is given by Smakhtin & Anputhas (2008). These flows also have an important function in the Cauvery delta against sea intrusion (Bandyopadhyay & Perveen 2008). Table 3 gives an overview of total water withdrawal in the basin, not taking into account hydropower, environmental flows, and losses through evaporation in reservoirs.

Table 2 | Irrigated area and water withdrawal for irrigation in the basin in 2000

Area (km^2)				Water utilization in 2000			
total	Under cultivation (net)	Equipped with irrigation infrastructure	Gross irrigated in 2000	Total (km^3)	As % of utilizable resources	Ground water share (%)	% of replenishable groundwater resources
89,490	41,545	17,288	19,000	19	60	48	75

Data sources: FAO (Figure 4), Central Water Commission and CWDT (2007a).

Table 3 | Freshwater resources (50% dependability) in km^3 and withdrawal (domestic and industrial projected for 2011, irrigation in 2000) in km^3 in the Cauvery river basin

Renewable freshwater resources	Total freshwater withdrawal	Freshwater withdrawals: Agriculture Amount	Agriculture Share (%)	Industry Amount	Industry Share (%)	Domestic Amount	Domestic Share (%)	Withdrawal as share of renewable resources (%)
31.3	21.1	19.1	91	0.7	3	1.3	6	67

Water quality

Cities and industries withdraw surface and groundwater for use but generally return more than 90% to blue water (non-consumptive use), often with degraded quality. In the Cauvery basin many domestic and industrial effluents are discharged untreated, polluting rivers, canals and groundwater. There is a large gap between wastewater generation and treatment capacity (Kumar 2009). Another major source for deteriorating water quality is agriculture. Within the Cauvery delta there is a salinity problem (fresh groundwater overlain by saline water). Water availability as described in the former chapters can diminish due to degraded water quality.

GENERAL SOLUTIONS

CWDT – integrated water resources management

The Inter-State Water Disputes Act of 1956 requires the government to encourage states to settle disputes through dialogue. When this is not possible, a tribunal is to be constituted, which makes a binding judgement after a hearing. The CWDT – set up in 1990 – passed an interim judgement in 1991 and declared a final award (allocation of Cauvery water to the different states) on 5 February 2007, based on normal availability (Salman 2002; Ghosh & Bandyopadhyay 2009). Nevertheless, irrigation demand exceeds allocated water availability during dry years. In the delta the summer crop depends on the timely release of waters from upstream areas. Downstream farmers argue that historically they have grown three crops annually. Upstream farmers argue it is unfair that they have to release water at a time when demand is highest. The fixation with absolute volumes of water is one of the contributing factors to the dispute. Proportionate sharing has the potential to allocate water equitably in both wet as well as drought years. Karnataka has already expressed its discontent to the press, stating that it would file a petition seeking review of the tribunal's final order. The process of adjudication through the tribunals in India is slow and may sometimes exclude the option otherwise available through cooperation (Tyagi 2003). In the past, large inter-state projects like the construction of a dam in one state and the benefits in another state have gone out of consideration, and techno-economically inferior solutions have had to be adopted. The River Boards Act 1956, which provides for a mechanism for managing inter-state rivers, has been ineffective in the implementation of an integrated water resources management (IWRM) approach on a basin or a sub-basin level. Although the National Water Policy also provides for River Basin Organizations, the mechanism has failed to evolve.

Within IWRM the whole watershed or basin must be considered. This concept has been developing since the beginning of the eighties, and makes us move away from top-down 'water master planning' to a more bottom-up planning and management approach. The latter implies the active participation of interested stakeholders. Keywords here are participatory irrigation management and water user associations (Narain 2000), practices already implemented in the Cauvery basin. The decision to manage water on the basin level is a political choice, and river basins thus become a scale of governance. The Water Framework Directive of the EU for example requires that water management be carried out at the scale of a river basin, particularly when this involves transboundary management. It is very likely that this will result in a shift in responsibilities of the institutions involved and the establishment of new institutions (Loucks & van Beek 2005). In different parts of the world various types of river basin organizations are implemented (Molle *et al.* 2007): basin authorities, basin commissions/committees or coordinating councils. The implementation of such an organisation is highly recommendable for the Cauvery basin.

Water availability and demand management

Literature on solutions and alternative policy options for future sustainable WRM in India include Gupta &

Deshpande (2004); Kumar *et al.* (2005); and Thakkar (2008). Sustainable WRM practices include the increasing of water supply and the managing of water demands. Applicable practices for the Cauvery basin are given in Table 4.

Water storage and rainwater harvesting

Due to the monsoonal characteristic of precipitation in the basin, the storage of water and rainwater is essential. As climate change will intensify precipitation events to shorter periods of time, the need for storage will become even larger. Both multipurpose dams and decentralized harvesting are thus a must (Chaturvedi 2001). In 2005, live storage capacities in the Cauvery basin (about 9 km^3) had the potential of storing 42% of average annual flow (21.3 km^3), which can be increased. Rainwater harvesting also prevents soil erosion. It can focus on (1) capturing water for domestic use (e.g. by rooftop rainfall collection); (2) replenishing green water (e.g. through stone bunds on the contour line); or (3) increasing blue water availability locally (e.g. through small check dams that increase recharge to the groundwater or store water in small reservoirs). Decentralized water harvesting is definitely an important factor for poor communities. However Kumar *et al.* (2006b) indicate the limitations of this practice. The storage of water should be implemented in the framework of IWRM, in order to avoid massive disproportional storage in upstream parts of the basin at the expense of downstream regions. Environmental flows should be maintained.

Table 4 | Supply increase and demand management practices applicable for the Cauvery basin

Supply-availability increase	Demand management
• Water storage and rain water harvesting	• Rehabilitation and modernization of existing infrastructure
• Artificial ground water recharge (AGWR)	• Increasing water productivity for agriculture (irrigated and rainfed)
• Reservoir management	• Economic instruments (e.g. water pricing)
• Water quality conservation and investment in wastewater infrastructure	• Restriction of water uses during drought periods
• Recycling of wastewater	• Changing food demand patterns
• Desalination	• Virtual water import–export
• Land use planning and soil conservation	

If suitable aquifers are accessible, AGWR has many benefits when compared to other storage options, e.g. low evaporation rates, natural treatment and storage capacity to buffer seasonal supply and demand variations. Gupta & Deshpande (2004) describe the potential for the Cauvery basin, based on its specific hydrogeology. Most of the basin is characterized by crystalline rocks, but the Cauvery delta has a large potential and need. Here the proportion of canal-irrigated areas has actually decreased at the expense of groundwater irrigation. The resulting depletion of the groundwater table (as observed the last years) – which could lead to the gradual intrusion of seawater in the delta – can be (partly) compensated by AGWR.

Reservoir management

Reservoir management needs to be sophisticated to maximize yield from a given catchment and storage combination; the desire to minimize evaporative losses, and the demand for optimum water quality outcomes. There should be a multipurpose controlled management for hydropower generation, other uses and flooding control.

Water quality conservation and investment in wastewater infrastructure

Water quality conservation and investment in wastewater infrastructure is a necessity in order to maintain the already quantitative scarce water availability. This includes the implementation of water pollution prevention strategies (legislation, polluting taxes, …) for the different polluters (Kumar *et al.* 2005). Society and individuals in India should have a greater knowledge and ability to bring about the required changes and mentality.

A general discussion on *recycling of wastewater* in India is given by Kumar (2009). Since both domestic and industrial water demands will increase substantially in the basin, so will the potential for recycled wastewater.

Desalination

In the Cauvery delta there are substantial deposits of brackish water in the underground. As the cost of desalinization is falling (Kumar *et al.* 2005), the prospects of desalinating brackish water – and also seawater for the coastal communities – are becoming more attractive.

Land use planning and soil conservation

Land use planning and soil conservation include a change of land use, reforestation and the reduced sealing of areas in order to prevent erosion and high surface flow coefficients.

Rehabilitation and modernization of existing infrastructure for domestic, industrial and agricultural water supply

Leakage reduction in domestic water use should be addressed Thakkar (2008) states that India has the largest irrigation infrastructure in the world, but its performance is amongst the poorest. The country average efficiency is about 40% for surface and 60% for groundwater irrigation (Singh 2007). As in the Cauvery basin, 91% of water use is for irrigation (and will stay high in future), an increase in irrigation efficiency (e.g. by installation of drip or sprinkler irrigation) can have a huge impact on reduced water demands. For 2050 realistic values are 60% for surface and 75% for groundwater irrigation (Gupta & Deshpande 2004). In 2001, about 18% respectively 15% of irrigated area in Karnataka respectively Tamil Nadu was under drip irrigation (Narayanamoorthy 2009). According to Thakkar (2008), for example, 90% of existing dams in India do not have a hydropower component. It is important to assess how many such existing dams can incorporate a hydropower component.

Increasing water productivity for agriculture (irrigated and rainfed)

Increasing water productivity for agriculture (irrigated and rainfed) includes (1) providing an appropriate quantum of fertiliser to the crop to realize yield potential; (2) cropping planning and diversification; (3) increasing the value per unit of water by integrating livestock and fisheries in irrigated systems; (4) appropriate timing and quantification of water delivery for the different growing stages of the plants. Quantification and timing of fertilization has to be managed carefully in order to avoid water pollution. At present, crop yields are low in India (e.g. 1,756 kg per ha for cereals during 2005–2006) as compared internationally (e.g. >5,000 kg per ha for cereals in France, Germany, USA and Japan in 1996). Cropping planning and diversification includes the growing of crops in regions where, or at times of the year when, ET requirements are lower. For the Cauvery basin, (Ghosh & Bandyopadhyay 2009) show the large differences in irrigation requirements for rice crops – a very water-intensive crop – during different times of the year. Other practices include the system of rice intensification (Thakkar 2008), a technique resulting in yields up to 8–10 tonnes per ha (tha) and reduced water requirements by over 50% (Senthilkumar *et al*. 2008). In 2002 average rice yield in India was 3 tha.

Economic instruments (e.g. water pricing)

According to Singh (2007), part of the reason for the low irrigation efficiencies is the highly subsidized price of irrigation water that encourages the excessive application of water to crops. An overview of potentials, problems and prospects for water pricing for irrigation is given by Reddy (2009).

Restriction of water uses during drought periods

Restriction of water uses during drought periods is a practice which is for example applied in Australia. During drought periods, there is a restriction on watering the garden or washing the car.

Changing food demand patterns

Influencing diets towards more water-efficient food mixes, such as less meat can be a demand management practice. However, the largest part of the population in the Cauvery basin is of Hindu religion, of which many are vegetarian. In both rural and urban India, the demand for food grains, especially for rice and coarse grains has been declining since the 1990s though, and the demand for non-grain food crops (vegetables, fruits, oil crops, …) and animal products (milk, chicken, eggs, fish, …) is increasing (Amarasinghe *et al*. 2008). Increasing income and urbanization will further increase the demand for non-grain food products in the Indian diet.

Virtual water import–export

Virtual water import–export is becoming an important concept for IWRM on a global and regional level, particularly in regions where water is scarce (Kumar & Jain 2007). The virtual water value, e.g. for paddy rice (2,850 m^3/tonne) – the major cereal consumed in Southern India – is high as compared with wheat (1,654 m^3/tonne) – the major cereal consumed in Northern India. At present, India is a net exporter of agricultural virtual water. Although India is self-sufficient in her food requirements, significant production surpluses and deficits exist in different river basins. In the context of national food self-sufficiency, the virtual water demand for food production will increase substantially by 2050. As pro capita water availability drops, there could be a certain point where sustainable river basin water management will not be possible any more due to agricultural water demands. Import of food would virtually equal the conservation of water, and should therefore be considered as a possibility (Falkenmark & Lannerstad 2007), especially as economic growth in India booms. India has a trillion dollar economy now and has large foreign exchange reserves (Amarasinghe *et al*. 2008). Within the Cauvery basin, industry is expanding and Bangalore is today one of the world IT capitals. As the country represents 2.4% of world land area, 4% of world water resources but 16% of the world population, food import is definitely defendable. A reasonable degree of food self-sufficiency in future however should be targeted because of the volatility in the food prices in the markets (Amarasinghe *et al*. 2008). A quantification of virtual water import and export in the Cauvery basin should be made.

National River Linking Project of India

The National River Linking Project (NRLP) of India (www.nwda.gov.in) foresees the linking of as many as 37 rivers, involving the construction of some 3,000 reservoirs, diverting in the order of 178 billion m^3 of water, installing 34 GW of hydropower capacity and irrigating 35 million ha (Misra *et al*. 2007). The water deficit Cauvery basin would be linked to the water surplus Mahanadi and Godavari basins. The fundamental idea is that water equity will be promoted through re-distribution from water rich to water poor areas in order to cope with future water challenges in India. Advantages and disadvantages are formulated by Misra *et al*. (2007). However, the project receives a lot of criticism from different authors (Bandyopadhyay & Perveen 2008). Critics argue that there are other solutions, which have not been properly considered. Gupta & van der Zaag (2008) assess the phenomenon of inter-basin water transfers from a multi-disciplinary perspective applied to the NRLP. The authors attempt to answer the question whether such transfers are compatible with the concept of IWRM. They make a poor evaluation of the NRLP to their five criteria.

CONCLUSIONS

This paper identifies the major challenges and possible general solutions for IWRM in the Cauvery basin in South India, which has a low per capita water availability and is shared by three states (Karnataka, Tamil Nadu, Kerala) and one Union Territory (Puducherry). Spatial and temporal distribution of precipitation is very uneven in the basin; as most precipitation falls during the monsoons and as the western part (the mountain range of the Western Ghats) receives a far larger amount than the eastern part. Water availability is expected to decrease due to climate change. The major part of the basin can be defined as semi-arid, which makes irrigation a necessity. Population densities are high, and due to population growth, urbanization and industrialization, domestic and industrial water demands will increase up to 2050. However, irrigation is by far the largest water demand stakeholder in the basin. Increasing irrigation water requirements have led to conflicts between the states of Karnataka and Tamil Nadu (especially during dry years). The CWDT was set up in 1990 to resolve these tensions. In 2007 the tribunal declared a final allocation of Cauvery water to the different states based on normal year water availability, but tension remains.

There is a need for IWRM on the basin level. The implementation of a river basin organization is highly recommendable. A combination of water supply increase and water demand management measures should be implemented to be able to cope with the future situation. Meeting domestic and industrial water needs will not be a problem. However, irrigation demands could still not be met, especially during dry years. Import of food should be considered as a possibility.

In order to analyse sustainable water management solutions for the current and future situation, a detailed assessment of water availability and demand – currently not available in the literature – should be made on the basin level. A hydrological model should be implemented, analysing current normal and dry year water availability as well as under climate change conditions. Virtual water flows to and from the basin and food requirements, should be analysed, in order to assess sustainable agriculture. Social and economic implications should be addressed. The combination of the described measures in this paper should be analysed. As a last option, the NRLP can be considered.

ACKNOWLEDGEMENTS

This work was presented at the Water Convention of the Singapore Water Week 2009.

REFERENCES

Alcamo, J., Flörke, M. & Märker, M. 2007 Future long-term changes in global water resources driven by socio-economic and climatic changes. *Hydrological Sciences Journal* **52** (2), 247–275.

Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. 1998 *Crop Evapotranspiration – Guidelines for Computing Crop Water Requirements*. FAO Irrigation and Drainage Paper 56, FAO – Food and Agriculture Organization of the United Nations, Rome.

Amarasinghe, U. A., Shah, T. & Malik, R. P. S. 2008 India's water futures: drivers of change, scenarios and issues. In: *Strategic Analyses of the National River Linking Project (NRLP) of India Series 1 – India's Water Future: Scenarios and Issues* (U. A. Amarasinghe, T. Shah & R. P. S. Malik, eds.). International Water Management Institute, Colombo.

Bandyopadhyay, J. & Perveen, S. 2008 The interlinking of Indian rivers: questions on the scientific, economic and environmental dimension of the project. In: *Interlinking Rivers in India: Issues and Concerns* (M. M. Q. Mirza, A. U. Ahmed & Q. K. Ahmad, eds.). Taylor and Francis, Abingdon.

Chaturvedi, M. C. 2001 Sustainable development of India's waters – some policy issues. *Water Policy* **3** (4), 297–320.

CWDT 2007a *Cauvery Water Disputes Tribunal – Volume V: Apportionment of the Waters of the Inter-State River Cauvery*. Cauvery Water Disputes Tribunal, New Delhi.

CWDT 2007b *Cauvery Water Disputes Tribunal – Volume II: Agreements of 1892 and 1924*. New Delhi.

Döll, P. 2002 Impact of climate change and variability on irrigation requirements: a global perspective. *Climatic Change* **54**, 269–293.

Falkenmark, M. & Lannerstad, M. 2007 Consumptive water use to feed humanity – curing a blind spot. *Hydrology and Earth System Sciences* **9**, 15–28.

Ghosh, N. & Bandyopadhyay, J. 2009 A scarcity value based explanation of trans-boundary water disputes: the case of the Cauvery River Basin in India. *Water Policy* **11**, 141–167.

Gosain, A. K., Rao, S. & Basuray, D. 2006 Climate change impact assessment on hydrology of Indian river basins. *Current Science* **90** (3), 346–353.

Gupta, S. K. & Deshpande, R. D. 2004 Water for India in 2050: first-order assessment of available options. *Current Science* **86** (9), 1216–1224.

Gupta, J. & van der Zaag, P. 2008 Interbasin water transfers and integrated water resources management: where engineering, science and politics interlock. *Physics and Chemistry of the Earth, Parts A/B/C* **33** (1–2), 28–40.

Hijmans, R. J., Cameron, S. E., Parra, J. L., Jones, P. G. & Jarvis, A. 2005 Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology* **25** (15), 1965–1978.

Kumar, M. 2009 Reclamation and reuse of treated municipal wastewater: an option to mitigate water stress. *Current Science* **96** (7), 886–889.

Kumar, V. & Jain, S. K. 2007 Status of virtual water trade from India. *Current Science* **93** (8), 1093–1099.

Kumar, R., Singh, R. D. & Sharma, K. D. 2005 Water resources of India. *Current Science* **89** (5), 794–811.

Kumar, K. R., Sahai, A. K., Kumar, K. K., Patwardhan, S. K., Mishra, P. K., Revadekar, J. V., Kamala, K. & Pant, G. B. 2006a High-resolution climate change scenarios for India for the 21st century. *Current Science* **90** (3), 334–345.

Kumar, M. D., Ghosh, S., Patel, A., Singh, O. P. & Ravindranath, R. 2006b Rainwater harvesting in India: some critical issues for basin planning and research. *Land Use and Water Resources Research* **6**, 1–17.

Kundzewitz, Z. W., Mata, L. J., Arnell, N. W., Doell, P., Kabat, P., Jiménez, B., Miller, K. A., Oki, T., Sen, Z. & Shiklomanov, I. A. 2007 Freshwater resources and their management. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden & C. E. Hanson, eds.). Cambridge University Press, Cambridge.

Loucks, D. P. & van Beek, E. 2005 *Water Resources Systems Planning and Management – An Introduction to Methods, Models and Applications*. UNESCO, Delft hydraulics, Paris, Delft.

Mahmood, A. & Kundu, A. 2008 Demographic projections for India 2006–2051: regional variations. In: *Strategic Analyses of the National River Linking Project (NRLP) of India Series 1 – India's Water Future: Scenarios and Issues* (U. A. Amarasinghe, T. Shah & R. P. S. Malik, eds.). International Water Management Institute, Colombo.

Misra, A. K., Saxena, A., Yaduvanshi, M., Mishra, A., Bhadauriya, Y. & Thakur, A. 2007 Proposed river-linking project of India: a boon or bane to nature. *Environ Geol* **51**, 1361–1376.

Molle, F., Wester, P. & Hirsch, P. 2007 River basin development and management. In: *Water for Food Water for Life - A Comprehensive Assessment of Water Management in Agriculture* (D. Molden, ed.). IWMI, Earthscan, Colombo amd London.

Narain, V. 2000 India's water crisis: the challenges of governance. *Water Policy* **2**, 433–444.

Narayanamoorthy, A. 2009 Water saving technologies as a demand management option: potentials, problems and prospects. In: *Strategic Analyses of the National River Linking Project (NRLP) of India Series 3 – Promoting Irrigation Demand Management in India: Potentials, Problems and Prospects* (R. M. Saleth, ed.). International Water Management Institute, Colombo.

Reddy, V. R. 2009 Water pricing as a demand management option: potentials, problems and prospects. In: *Strategic Analyses of the National River Linking Project (NRLP) of India Series 3 – Promoting Irrigation Demand Management in India: Potentials, Problems and Prospects* (R. M. Saleth ed.). International Water Management Institute, Colombo.

Salman, S. M. A. 2002 Inter-states water disputes in India: an analysis of the settlement process. *Water Policy* **4** (3), 223–237.

Senthilkumar, K., Bindraban, P. S., Thiyagarajan, T. M., de Ridder, N. & Giller, K. E. 2008 Modified rice cultivation in Tamil

Nadu, India: Yield gains and farmers' (lack of) acceptance. *Agricultural Systems* **98** (2), 82–94.

Siebert, S., Döll, P., Hoogeveen, J., Faures, J.-M., Frenken, K. & Feick, S. 2005 Development and validation of the global map of irrigation areas. *Hydrology and Earth System Sciences* **9**, 535–547.

Singh, K. 2007 Rational pricing of water as an instrument of improving water use efficiency in the agricultural sector: a case study in Gujarat, India. *Water Resources Development* **23** (4), 679–690.

Smakhtin, V. & Anputhas, M. 2008 An assessment of environmental flow requirements of Indian river basins. In: *Strategic Analyses of the National River Linking Project (NRLP) of India Series 1 – India's Water Future: Scenarios and Issues* (U. A. Amarasinghe, T. Shah & R. P. S. Malik, eds.). International Water Management Institute, Colombo.

Thakkar, H. 2008 Future water solutions for India. *Development* **51**, 68–71.

Tyagi, A. C. 2003 *State of India's Water*. Third World Centre for Water Management, Atizapán, Mexico.

UNEP 1992 *World Atlas of Desertification*. Edward Arnold, London.

Viviroli, D. & Weingartner, R. 2004 The hydrological significance of mountains: from regional to global scale. *Hydrology and Earth System Sciences* **8** (6), 1016–1029.

Webster, P. J., Magana, V. O., Palmer, T. N., Shukla, J., Tomas, R. A., Yanagi, M. & Yasunari, T. 1998 Monsoons: processes, predictability and the prospects for prediction. *Journal of Geophysical Research* **103**, 14451–14510.

First received 2 December 2010; accepted in revised form 14 February 2011