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Over Dependency on Groundwater in India: Issues and Insights

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Abstract

Background: India witnessed a sharp decline in rainfall during the decades of 1991-2000 and 2001-2010. But rainfall started improving during the decade 2011-2020 and by the year 2020, the annual rainfall of the country almost became equal to the long period average annual rainfall. Although overall rainfall improved, yet, the present analysis shows that in general, the states in northwest and central India, like Punjab, Haryana, and Uttar Pradesh are facing a remarkable downward trend in seasonal (monsoonal) and annual rainfalls both. The states of the western region of the country, like Rajasthan and Gujrat, are witnessing an upward trend in both seasonal (monsoonal) and annual rainfalls. States of southern India are not much affected.

The present analysis also shows that despite no significant change in the net annual groundwater recharge and annual groundwater draft from 2004, the numbers of over-exploited, critical, and semi-critical blocks rose exponentially after 2011. Further, different groundwater assessments from 2004 show no significant increase in annual groundwater draft, according to a report of the United Nation, groundwater abstraction continued to rise sharply in India. Thus, there seems no compatibility between annual rainfall, annual recharge, annual draft, and numbers of OCS blocks indicating serious discrepancies in groundwater assessment methodology and requiring a serious review of groundwater assessment methodology and norms being adopted in various states of India. Due to declining rainfall in some of the major food grain-producing states, the balance of water distribution in the country is shifting and it may become more prominent in the years to come. India is already the largest abstractor of groundwater in the world and in the above scenario, there will be tremendous pressure on groundwater in the future. The suggested actions which may counter the looming crisis in the country, particularly in north-western and central Indian states, include increasing forest cover up to 20% in the next 25 years in poorly forested states, limiting area under water-guzzling greenhouse producing gas crops, starting land subsidence survey in cities, limiting groundwater abstraction and injecting water into aquifers, launching group schemes of drip and sprinkler irrigation on a large scale using existing tube-wells/wells, searching the alternative source of wastewater by developing integrated facilities to retrieve, treat, store, and transport wastewater, transferring groundwater from groundwater surplus areas to scarce areas enacting comprehensive central law on groundwater, improving water and agriculture resource efficiency through the Internet of Things, cloud and sensor-based network, mapping and time-bound renovation of large traditional water bodies (>1 hectare), revisiting groundwater assessment methodology and norms, quantifying static groundwater resource, developing heat tolerant and less water consuming crops and changing food habits.

Keywords: Irrigated area • Decennial rainfall • Rainfall trend • Rainy days • Groundwater availability • Abstraction, • Abstraction rate • Recharge and draft • Growth of OCS blocks • Forest cover • Traditional water bodies • Reuse of wastewater • Water laws • Automation in irrigation • Water transport.

Introduction

Groundwater, which fetches the primary needs of many sectors in India, is heavily under pressure. There is overdependence on groundwater to meet the ends with regards to irrigation, industry, domestic and drinking water, etc. About 80% of India`s drinking water needs depend on groundwater. About 2/3 of water for irrigation is supplied by groundwater and 84% of the total addition to irrigation over the last four decades has come from groundwater. About 60% of India`s districts face groundwater exploitation and/or serious quality issues [1, 2].

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Methodology

Agriculture is the biggest Consumer of Groundwater accounting for 91% of withdrawals every year, while domestic and industrial withdrawals account for the remaining 9%. About 63% of irrigated area in the country is attributed to groundwater as is clear from Table 1 [3].

Out of the total irrigated area of 68.445 million hectares, the area irrigated from groundwater is 43.02 million hectares or 62.85%.

India is the largest groundwater user in the World, using nearly a quarter of the global total. This is partly because of decentralized access to water in the country. The "Niti Aayog", the highest policy-making body in the country, recognizes that groundwater is being exploited beyond sustainable levels.

Table 1. Area Irrigated by different sources in India.

Name of Source	Irrigated area (Million hectares)
Government Canals	16.02
Private Canals	0.163
Tanks	1.723
Tube-wells	31.666
Other wells	11.354
Other sources	7.519
Total	68.445

According to the Central Groundwater Board water level in 56% of the wells in the country declined in 2013, compared to the average of the preceding decade (2003-12).

Weak monsoons due to climate change have further eroded groundwater resources. Groundwater mainly depends on rainfall for recharge. So, deficient rain means less groundwater availability. A failed monsoon leads farmers to draw deeper from groundwater to irrigate their crops, which pushes water levels down further. Key agricultural areas of Punjab and Haryana, the major contributor to the food basket of the nation received half the normal rainfall recurrently over the past 16 years. Punjab, according to Indian Metrological Department figures, has had only two normal monsoon rainfalls since 1999. In Haryana, rain has been above normal in just four of the last 16 monsoons. In the future, this pattern of rainfall will have a serious adverse impact on agriculture which is heavily dependent on groundwater. With an estimated 30 million Groundwater structures in play, India may be hurtling towards a crisis of over-extraction and quality depreciation of groundwater. Despite being the lifeline of India's water supplies, groundwater is overlooked by policymakers and users alike. If current trends continue, within 20 years 60% of all aquifers in India will be in critical condition [4].

Despite its overexploitation and declining quality groundwater will remain an assured source of irrigation water supplies in the future if managed carefully. Groundwater's universal presence and unique buffer capacity have enabled people to settle and survive in dry areas where rainfall and run-off are scarce and unpredictable. Groundwater is a reliable source of water supply and it has contributed to significant social-economic development and poverty alleviation and will continue to do so. Groundwater is also likely to play a crucial role in the context of climate change mitigation and adaptation. In many water-scarce regions, climate change is expected to result in reduced and more erratic surface water and groundwater availability. Groundwater recharge will decrease in these areas as well, but groundwater storage buffer will in most cases ensure uninterrupted water availability, thus triggering a shift in withdrawals from surface water to groundwater. This will reduce overall water supply risks and suggest that groundwater in such regions will provide the key to coping with water scarcity problems imposed or aggravated by climate change during the 21st century [5]. This paper tries to examine the present status of groundwater in India, the problems it faces today and suggest remedies to carefully manage it in the scenario of climate change.

Declining and unpredictable rainfall

Growing demand due to increasing population coupled with the weakening of monsoon in certain parts of India due to climate change is responsible for groundwater depletion. Key agricultural areas in the country like Punjab, Haryana, Western and Central Uttar Pradesh, etc. are facing the problem of weak monsoon recurrently, resulting in less groundwater recharge and depletion of the groundwater resource.

Figure 1 shows the decennial rainfall in India from 1981 to 1990 decade. It indicates that the rainfall in the country started decreasing sharply during the decade 2001 to 2010. It improved somewhat during the decade of 2011-2020 though still below the long period average annual rainfall [6-8].

But in major food-grain producing areas situation is graver. In Punjab, the mean annual rainfall for the period 1989-1918 was 538.6 mm, about 17% less than the long period average rainfall of 649 mm. Both seasonal (monsoonal) and annual rainfalls show a decreasing trend [9,10]. In most of the districts of the state, the annual numbers of rainy days were in the range of 16-33.3 only [9]. The simple average comes out to be 30.46 days. In the state of Haryana, the mean annual rainfall for the said period was 499.7 mm only, about 19% less than the long-period average rainfall of 617 mm. Both seasonal (monsoonal) and annual rainfalls show a declining trend [11,10].

In most of the districts of the state, the annual numbers of rainy days were in the range of 20-29 only [11]. The simple average comes out to be 31.46 days. In the state of Uttar Pradesh, the mean annual rainfall during the 2001-2010 decade was 17.77% less than the long period average rainfall. In its Bundelkhand region, this figure was 24.44% [12]. An analysis of rainfall data for the period 1989 to 2018 shows that the monsoon season and annual rainfalls in the state have a significant decreasing trend. In general, districts over the northeast of the state (except Kushinagar and Ballia) received a high amount of rainfall, and districts over the southwest of Uttar Pradesh received less amount of rainfall. The mean annual rainfall for the period 1989-to 2018 was 748.1 mm only, 23.22% less than the long-period average rainfall of 974.4 mm [10,13]. In most of the districts, the numbers of rainy days were in the range of 31.2-41.2. In some of the western districts, this figure was only 27, and in the most productive belt of western & central Uttar Pradesh, this range is only 27-34.6 [13]. The simple average comes out to be 36.18 days. In the state of Madhya Pradesh, the mean annual rainfall for the period 1989-2018 was 997.8, about 1.88% below the long-period average rainfall of 1017 mm. Both seasonal and annual rainfalls show decreasing trends [10,14].

In most of the districts, the annual numbers of rainy days were in the range of 36-48 [14]. The simple average comes out to be 42.12 days. In the state of Maharashtra, the mean annual rainfall for the period 1989 to 2018 was 1146.5 mm, about 2.1% below the long-period average rainfall of about 1455.5 mm. However, seasonal (monsoonal) rainfall has no trend. Annual rainfall shows a mild declining trend [10,15]. In most of the districts of the state, the annual numbers of rainy days were in the range of 37-54 [15]. The simple average comes out to be 58.2 days. In the state of Bihar, the mean annual rainfall for the said period was 1098.9 mm, about 7.3% less than the long-period average rainfall of 1186 mm. Both seasonal (monsoonal) and annual rainfalls show declining trends [10,16].

In most of the districts of the state, the numbers of rainy days were in the range of 36-46.2 [16]. The simple average comes out to be 48.5 days. In the state of Gujrat, the mean annual rainfall for the period 1989 to 2018 was 772.4 mm, about 8.3% less than the long-period average rainfall of 842.5 mm. A remarkable feature is that both seasonal (monsoonal) and annual rainfalls show an upward trend [10,17]. In most of the districts, the annual numbers of rainy days were in the range of 22-35.3 [17]. The simple average comes out to be 38.74 days. In the state of Karnataka, the mean annual rainfall for the period 1989 to 2018 was 1146.9, about 8.1% less than the long-period average rainfall of 1248 mm. Both seasonal and annual rainfalls show a downward trend, though these are not very sharp [18,19]. In most of the districts, the numbers of rainy days were in the range of 32-61.2. In some districts, it was as high as 89.8-105 [19]. The simple average comes out to be 58.9 days.

In the state of Tamil Nādu, the mean annual rainfall for the period 1989-2018 was 898.1 mm, about 10% less than the long-period average rainfall of 998 mm. Both seasonal (monsoonal) and annual rainfalls almost do not show any trend, meaning thereby that average rainfall in this period remained constant in the state [10,20]. Another distinguishable feature in the state is that the difference between seasonal and annual rainfall is comparatively high.The

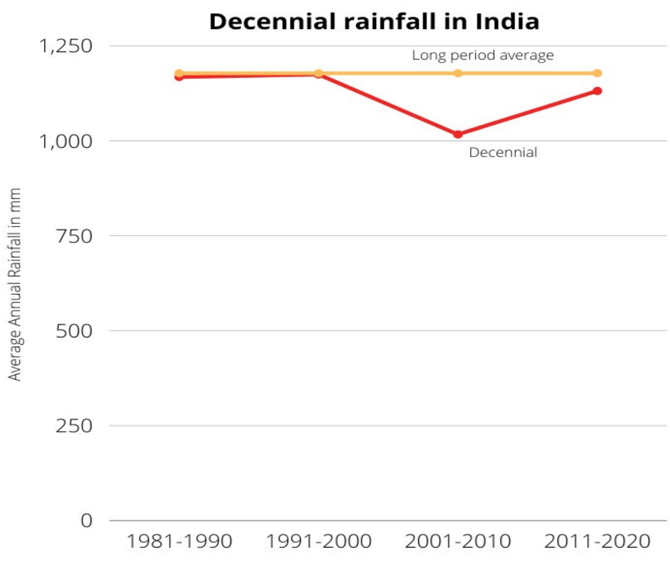

Figure 1. Decennial rainfall in India

numbers of rainy days in the majority of the districts were in the range of 34-51.3 [20]. The simple average comes out to be 48.48 days.

In the state of Telangana, the mean annual rainfall for the period 1989 to 2018 was 905.1 mm, about 5.8% less than the long-period average rainfall of 961 mm. Both seasonal and annual rainfalls show declining trends though not so sharp [10,21].In most of the districts, the numbers of rainy days were in the range of 36-44.89 [21]. The simple average comes out to be 43.47 days. In the state of Andhra Pradesh, the mean annual rainfall for the period 1989 to 2018 was 903.6 mm, about 6% less than the long-period average rainfall of about 961 mm. The seasonal (monsoonal) rainfall in the state shows an upward trend though very little, while annual rainfall shows a downward trend [10,22]. The range of the number of rainy days in most of the districts of the state was 32-50.2. The simple average comes out to be 47.8 days. In the state of Rajasthan, the mean annual rainfall was 454.9 mm, about 7.9% less than the long-period average rainfall of 494 mm. Both seasonal (monsoonal) and annual rainfalls show upward trends [10,23]. The number of annual rainy days in most of the districts of the state ranged from 23.5 to 34.2 [23]. The simple average comes out to be 28.8 days.

From the above narrations it may be concluded that, in general, the states in northwest and central India, like Punjab, Haryana, and Uttar Pradesh are facing the problem of a decline in seasonal (monsoonal) as well as annual rainfalls. These states are major contributors to the food basket of the country. In the states of the western region of the country, like Gujrat and Rajasthan, upward trends in the seasonal (monsoonal) and annual rainfalls have been observed. In the southern states like Karnataka and Telangana decline in rainfall is mild while in Tamilnadu no decline in rainfall is observed. In Andhra Pradesh seasonal rainfall shows a little upward trend, but annual rainfall shows a little downward trend. The number of rainy days in the major food grain-producing states is comparatively low. Thus, the pattern and distribution of rainfall are changing in the country and it is shifting from the major food grain-producing areas. Therefore, in the future, these areas will face the problem of less groundwater availability and enhanced groundwater abstraction.

Status of groundwater in India

Northern India is very rich in groundwater resources and has a large groundwater reservoir. According to the latest assessment total dynamic groundwater recharge of the country as of March 2020 was, 436.7 BCM of which 397.62 BCM is extractable. Out of this, 244.92 BCM is being abstracted including drinking water, domestic, and industrial use, leaving 122.70 BCM for future development [24]. But this large groundwater reservoir has made India the world`s highest and most reckless user of groundwater. Table 2 shows the ten top groundwater abstracting nations [5].

About 72% of global groundwater abstraction takes in these ten countries. Table 2 indicates that India`s annual abstraction of groundwater is more than the combined annual abstraction of China and the USA. It is pertinent to mention here that despite a higher population than India, the annual abstraction of groundwater in China is only 44.6% of India`s annual abstraction. This shows how much India depends on groundwater to fulfill its water needs. Further, groundwater abstraction rose sharply in India after the tube-well revolution in ninety's, and still growing, the groundwater abstraction curve almost became flat by 2010 in China and the USA as depicted in Figure 2 [5].

Table 2. Top ten groundwater abstracting nations

Country	Abstraction (Km^3/year)
India	251
China	112
United States of America	112
Pakistan	64
Iran	60
Bangladesh	35
Mexico	29
Saudi Arabia	23
Indonesia	14
Italy	14

Source; [5]

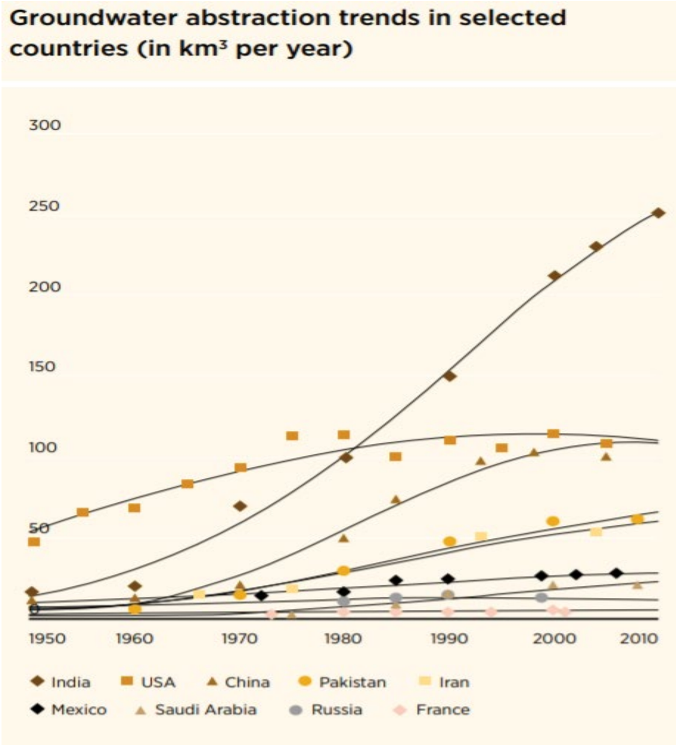

Figure 2. Groundwater abstraction trend in selected countries Source [5].

Groundwater availability in India

The periodic assessments carried out from the year 1975 show significant changes in groundwater recharge and abstraction. A marked increase in groundwater abstraction was observed which was mainly attributed to the extensive groundwater development in the country to meet the growing demand for irrigation water in the agriculture sector. Groundwater abstraction for domestic and industrial use also increased. However, from the 2004 assessment onward, a marginal increase in groundwater abstraction was observed and from the 2017 assessment, it started declining as is indicated in Table 3 [24-29].

Though there is no significant change in the annual groundwater recharge and abstraction in the country since 2004, numbers of over-exploited, critical, and semi-critical block/areas or OCS blocks/areas were persistently increasing since 2009. In 2009, their number was 1341 which rose to 2441 in the 2020 assessment as shown in Figure 3.

Rainfall also does not show any significant change during this period, rather there is some declining trend. Moreover, according to the United Nation, the abstraction rate in the country was rising as shown in Figure 2. Therefore, the categorization of OCS blocks is not compatible with the net annual groundwater recharge, annual groundwater draft, and annual rainfall data. There may be the following reasons for it:

1. There may be discrepancies in the new Groundwater Estimation Committee-2015 norms or the values of different variables like specific yield, the unit draft of groundwater structures, recharge from rainfall and other sources, etc. for assessing the groundwater resource.
2. This may be due to regional variations and the fact that these blocks are concentrated in certain states, mainly the northwest region and northcentral region of the country. Table 4 shows the percentage of these in some states [29].

The state of Punjab, a major producer of cereal crops is worst affected and recklessly withdrawing groundwater as 80.42% of its blocks are in OE/

Table 3. Groundwater availability from 2004 BCM (Billion Cubic Meters).

As on	Net annual groundwater availability or recharge	Annual groundwater draft or abstraction	Abstraction %
Mar-04	399	231	58
Mar-09	396	243	61
Mar-11	398	245	62
Mar-13	411	253	62
Mar-17	392.7	248.69	63.33
Mar-20	397.2	244.92	61.6

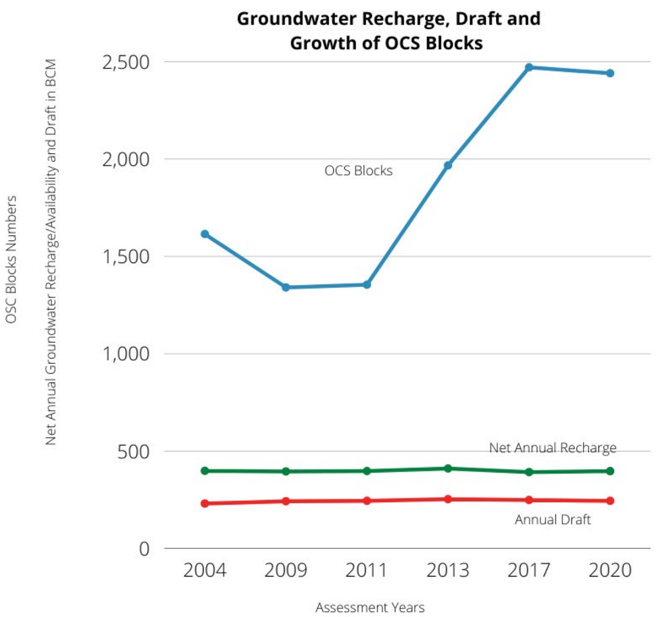

Figure 3. Net annual groundwater recharge, abstraction, and growth of OCS blocks from 2004.

Critical category. In Haryana, another major producer of cereal crops, 63.20% of blocks are in OE/Critical category. In southern India also the situation is worsening. In Tamilnadu, 46.39% of blocks are in OE/Critical category. In a state like Uttar Pradesh, rich in water resources 15.73% of blocks are in the OE/Critical category and the problem is worsening continuously. In the 2004 assessment, 158 blocks were in the OCS category which rose to 282 in the 2020 assessment.

Thus it can be concluded that despite no significant change in overall net annual groundwater recharge, abstraction, and rainfall in the country from 2004, the number of problematic blocks or OCS blocks increased substantially since 2004 and it needs to be further analyzed why this is happening. Ideally, in such a scenario, the number of OCS blocks should not have changed substantially. This also indicates the over-dependency of irrigated agriculture on groundwater resulting in groundwater depletion in certain food grain-producing states of the country. This will further aggravate in the future as the effect of climate change will be felt primarily through the water (Figure 4).

Static groundwater resource

There is no authentic assessment of static groundwater resources or fossil groundwater resources or non-renewable groundwater resources in the country, though groundwater estimation guidelines mandate it. However, there is a consensus that the country has a sizeable static groundwater resource. This resource is not an active part of the current hydrological cycle but is a reserve and acts as an additional source of water in the dry season or dry years. The quality of this resource is yet to be assessed. Being a non-replenish able reserve it may have serious quality issues. Moreover, it is a reserve and cannot be a source of regular water supplies. It should be used very cautiously and in emergencies only.

Reliability of groundwater assessments

Rainfall is the dominant source of annual groundwater replenishment, though its availability in time and space remains non-uniform because of varied hydrogeological and other factors. Therefore, the sustainable utilization of groundwater resources demands a realistic assessment based on certain scientifically prescribed procedures. To derive a uniform pattern and procedure for the periodic assessment of groundwater resources at the National level, a detailed methodology was evolved by Groundwater Estimation Committee (GEC), set up by the Government of India in1996. The procedure set up by this committee to assess groundwater resources was named as GEC-1997 Methodology.

The dynamic groundwater resource estimation provides baseline data on recharge and extraction components of groundwater. Based on these, the resource assessment units (blocks, watersheds, talukas) are classified into safe, semi-critical, critical, and overexploited categories for groundwater utilization and its management. The methodology involves a comprehensive exercise, entirely based on a variety of data sets and various assumptions/ad Hoch norms, primarily used to estimate rainfall recharge, and recharge from other sources like irrigation, water conservation, and storage structures, and the groundwater extraction for different uses. These large data sets are collected from different sources, therefore ensuring the authenticity of such data is an uphill task for the agencies engaged in resource estimation. It has been observed that any variation, deviation, gap, or inconsistency in any data or any discrepancy in assumed norms/parameters may lead to distortion of resource assessment figures. Even a slight variation or incorrectness in the data and the discrepancy in the adopted norms, in the absence of field validation, may change the recharge and extraction figures drastically leading to faulty groundwater assessment and a different overall resources scenario coupled with the wrong categorization of assessment units. Therefore, groundwater resources if not estimated correctly may seriously jeopardize groundwater development and management strategies.

The GEC-97 Methodology was used for periodic groundwater resource assessments in the years 2000, 2004, 2009, 2011, and 2013. However, later on, this 1997 methodology was slightly modified and named as GEC-2015 Methodology. This modified methodology categorized the whole country into 42 Major Aquifers by prescribing and recommending different sets of specific

Table 4. Percentage of OCS blocks/areas in some Indian states as on .

Name of state	Percentage of OCS blocks/areas	Percentage of OE/Critical blocks/areas
Punjab	84.05	80.42
Haryana	79.6	63.2
Rajasthan	85.08	74.22
Tamil Nadu	63.46	46.39
Uttar Pradesh	34.14	15.73

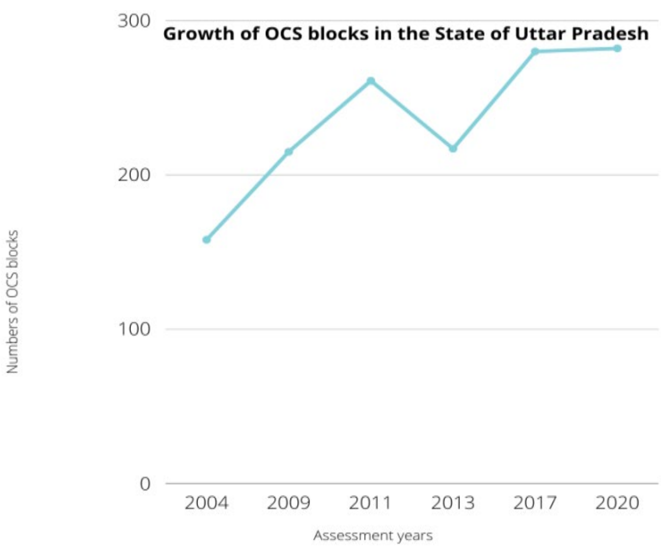

Figure 4. Growth of OCS blocks in the state of Uttar Pradesh.

yield and rainfall infiltration factors for these aquifers. Further, it dropped the most important criterion of groundwater level declining trend prescribed earlier in the GEC-1997 Methodology for categorization of assessment units. It also included an ad-hoc procedure for groundwater resource assessment in urban areas. The GEC-2015 Methodology was used in the groundwater resources assessments of 2017 and 2020 [30].

To check the reliability/authenticity of groundwater estimation, groundwater recharge and extraction figures of groundwater assessments in the state of Uttar Pradesh for the years 2013, 2017, and 2020 were analyzed in which many discrepancies and variations in reported and assessed figures have been noticed. Some of the key observations are:

1. GEC-2015 methodology recommends an average specific yield of 6% for older alluvium which covers most of Uttar Pradesh. But so far in all the previous assessments for the state of Uttar Pradesh, the specific yield was taken as 16% for most alluvium blocks and 10/12% for a few blocks for computing rainfall recharge [31]. As a result, rainfall recharge values have been reported to be much higher side raising doubts about the reliability and authenticity of resource assessments.
2. For estimating groundwater extraction from irrigation uses, annual unit draft values of different types of irrigation wells are being assumed which do not match with their actual withdrawals. For example, in the districts of Sambhal and Amroha, having similar hydrogeological conditions and cropping patterns, the annual unit draft for private deep tube wells in the non-monsoon season has been taken as 1.5 ham and 4.5 ham respectively in the 2017 assessment which seems unrealistic as conditions are same. Similarly, for State Tube Wells also different values of the annual unit draft have been assumed which should have been the same seeing the similar conditions in these two districts [31]. Thus, there seem large variations between the assumed figures and actual figures of unit drafts making groundwater assessment less reliable. The unit draft of these structures should be assessed periodically in actual field conditions and accordingly, the assessed values should be adopted for estimation.
3. Similarly, the assessed values of groundwater extraction for domestic uses have been found on the lower side. The analyses of extraction data for drinking water uses revealed that in the 2017 assessment the reported figure is 4.95 BCM, while the field data suggest that the actual extraction was 5.49 BCM [32].
4. A significant amount of groundwater is also being extracted for industrial, infrastructural, and commercial uses, but this component of extraction has not been computed and considered in the resources assessments. The available information reveals that these sectors are using about 9.3 BCM of groundwater annually in the state of Uttar Pradesh only [32]. However, the actual figures may be much more.
5. The urban assessment norms for recharge estimation suggested by the GEC-2015 methodology do not match the actual field conditions. In the methodology, a 30% rainfall infiltration factor is proposed as an ad-hoc arrangement but considering highly concretized land use in most of the urban areas, this figure appears to be on the very higher side and unrealistic. Similarly, the computation of recharge from other sources such as losses due to seepage from pipelines, sewage, and flash floods appears unrealistic.
6. It has also been found that by not accounting for the groundwater decline in the categorization of assessment units, some assessment units, despite being categorized as overexploited or critical; do not have any declining trend in groundwater levels indicating ambiguity in the GEC-2015 methodology. For example, despite showing a rising trend in groundwater levels, Pryagraj and Varanasi cities in Uttar Pradesh are categorized as over-exploited [31].So in light of the above, it can be argued that the GEC-2015 methodology needs to be re-examined and thoroughly reviewed to ensure the reliability of groundwater resources assessments.

Groundwater in Urban areas

All prominent urban areas are severely affected by groundwater depletion. In these areas, groundwater is likely to become a critically scarce resource, as the mining of static groundwater reserves has already started, which is a serious issue and needs urgent attention. For example, monitoring of groundwater levels in 22 prominent cities of the state of Uttar Pradesh shows that groundwater level is declining at a rate of 0.5 m per year to more than 01 m every year in cities like Lucknow, Kanpur, Meerut, Noida, and Ghaziabad. Based on the past trend of groundwater decline, the average yearly declines in some of the prominent cities of the state are shown in Figure 5 [1]. Land subsidence due to groundwater pumping is a problem threatening several Indian cities. Many Asian cities like Beijing, Jakarta, Dhaka, Bangkok, Ho Chi Minh, and Shanghai in the recent past and Tokyo in the 1960s-1970s have all faced the problem. Experts now predict that Indian cities also are likely to face land subsidence if the over-exploitation of groundwater continues unchecked. Lucknow is under threat of massive subsidence (land shrinking) from over-exploitation of groundwater resources in the next 15 to 20 years [2]. There is a strong relationship between the rate of net groundwater pumping and the rate of land subsidence. Therefore, a key factor in preventing land subsidence in Indian cities is to control the rate of net groundwater pumping. Authorities controlled the land subsidence in Shanghai by effectively limiting the groundwater withdrawal and recharging the aquifers by injecting water [33].

Forest cover and water

Now there is a growing consensus that precipitation and vegetation have a strong correlation. Forests and trees have an impact on the water cycle and influence climate through atmospheric water cycle controls. Forest plays a significant role in determining rainfall. Even localized forest loss can sometimes bring a wet region to arid conditions. Large-scale deforestation decreases evapotranspiration and precipitation and increases runoff over the deforested region.

An analysis of the districts of the Bundelkhand region of the state of Uttar Pradesh shows that there is a strong correlation between forest cover and negative deviations in rainfall. It indicates that negative deviation in rainfall decreases with an increase in forest cover as in the districts having nearly 6% or less forest cover negative deviations are much more than the districts having nearly 10% or more forest cover [12]. The Nation`s forest policy declared after independence envisaged developing forest cover in one-third of the land area. Forest cover in India (2021) is 712249 Km^2 which is 21.67% of the total geographical area of India. India has added 3976 sq. km of forest cover from 2017 to 2019 but it is confined to three states namely; Karnataka, Andhra Pradesh, and Kerala only. In the three main grains-producing states of Punjab, Haryana, and Uttar Pradesh the forest cover is only 3.47, 3.62, and 6.15 percent respectively much below the national average [34], and in these states, the negative deviation in rainfall is -17%, -19%, and -23.22% respectively, highest among the analyzed states. These are the states where

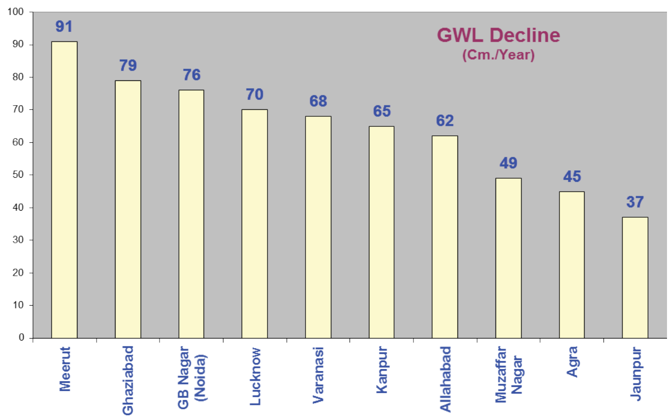

Figure 5. Average decline of groundwater levels in some of the prominent cities of Uttar Pradesh.

comparatively sharp downward trends have also been observed in seasonal (monsoonal) and annual rainfalls. In these states number of rainy days are also comparatively much less than in the other states. Thus, the above analyses suggest that in these states groundwater resources will further shrink in the future jeopardizing the food security of the country. It has already started in Punjab, Haryana, and Uttar Pradesh and these states need immediate action for groundwater restoration.

Action for groundwater restoration

To meet the future challenges of groundwater restoration and protection, a complete overhaul of groundwater policy and management strategy is required and there is a need to act according to a long-term vision which may include the following aspects:

1. There is no compatibility between the growth of OCS blocks/areas and rainfall, net groundwater recharge, and abstraction. Moreover, groundwater withdrawal data reported in the report of the United Nation and worked out in periodical assessments do not match indicating anomalies in the data. So first and foremost requirement is making an accurate and reliable assessment of groundwater. Wrong and inaccurate data may lead us to prepare wrong plans making management and restoration of groundwater resources, a remote possibility. In the light of discussions of para 3.2, there is an urgent need to revisit the Groundwater Estimation Committee methodology and estimation norms, values of various variables like specific yield, the unit draft of abstracting structures, monsoon, and non-monsoon recharge factors, etc. Further to ascertain whether the groundwater recharge values are realistic or not, counterchecking in 5% of assessment units should be done by adopting the nuclear isotope technique.

2. Though there are global factors responsible for shifting rainfall patterns, increasing forest cover at the local level is within our capabilities and this intervention only can make a great difference and may be very effective in blunting the sharpness of climate change by increasing rainfall and groundwater restoration. So in the states where forest cover is below 10%, mainly Punjab, Haryana, and Uttar Pradesh efforts should be made to increase forest cover by 20% in the next 25 years. An action plan should be made to develop forest areas in every village so that forest cover is evenly distributed within the states. Special laws can be promulgated for this and if the land is not available, it may be acquired. To implement this approach, independent authority can be created. The latest technologies to develop forests rapidly may also be included.

3. To check over-exploitation of groundwater agricultural practices needs to be changed in the problematic states like Punjab, Haryana, and Uttar Pradesh by controlling and restricting area under water-guzzling crops like Sugarcane, Wheat, and Rice. If needed special laws can be promulgated for this.

4. Modern irrigation methods like sprinklers and drips can improve water efficiency substantially and save a lot of water. Though to promote these systems, subsidy-based individual schemes are being executed for the last 30 years; their impact is negligible as only about 5% of minor irrigation structures in the country use these systems [1]. There are plenty of tube wells for irrigation in the problematic states like Punjab, Haryana, and Uttar Pradesh on which these systems can be installed. To increase coverage of these systems, community schemes that can use these tube wells/wells are to be conceptualized and implemented. To promote drip irrigation on a large scale, cultural practices are to be changed for which community schemes like “Horticulture Parks” can be introduced.

5. To reduce pressure on groundwater, irrigation efficiencies, as well as resource efficiency in agriculture, are to be improved considerably. Automation in agriculture and irrigation is one way to improve efficiencies. So, ITO (internet of things), cloud and sensor network-based automated irrigation systems, and automated agriculture should be introduced. An action plan to introduce these technologies on a large scale is needed now.

6. Another time-tested method to reduce dependency on groundwater in problematic areas may be the transfer of water from surplus areas to scarce areas. A commonly used method is the inter-basin transfer of surface water. But in waterlogged areas, there is surplus groundwater also which can be drained from the root zones up to desired levels through a combination of sub-surface field drains and surface drains and collected in large sump wells, from where this water can be lifted and transported to water-scarce areas. This will also lower the groundwater levels of the area and reduce waterlogging which will result in improving crop productivity. There are varying estimates of waterlogged areas in the country and consensus is yet to be reached but it is a sizeable area [1]. Thus, the above concept may be an effective solution for groundwater restoration and should be tried and tested.

7. In urban areas, the first step needed urgently, is to start a land subsidence survey, and to begin with metropolitan and prominent cities of the country can be selected for it. If in these cities land subsidence is found more than 10 mm per year, extensive control on groundwater extraction and recharge of groundwater aquifers by pumping water artificially and other measures should be taken up. The policy of vertical development in cities needs a relook as it is not climate-friendly and almost eliminates natural recharge sheds. It also encourages overexploitation of groundwater as high-rise buildings and skyscrapers draw much more groundwater per unit area in comparison to traditional buildings. So Instead of a policy of vertical development, a policy of horizontal development needs to be encouraged.

8. Local surface water storage will be more relevant in the future to sustain agriculture and groundwater resources. So, the traditional ways of rainfall capture and retention such as farm bunds, trenches, ponds, surface water bodies, etc. are to be revived on a large scale.

9. Water supply can be effectively improved through traditional water bodies/ponds, most of which are currently in very dilapidated conditions. Traditionally, every village had more than one pond, and they are still plenty in rural areas. Storage and recharge capacities of most of these have reduced substantially due to heavy siltation over time and encroachment due to expansion in agriculture and urbanization. Some of these ponds are small and can be developed manually under MNREGA. But many are too big to be redeveloped manually due to heavy earth movement and require heavy earth moving equipment for redevelopment and restoration. So, there is a need to map all the ponds greater than one hectare in the state and prepare a time-bound action plan to redevelop and restore these as water sanctuaries.

10. There is also a need to review groundwater`s legal and constitutional status and enact a central law to manage Nation`s groundwater effectively. Many states have enacted acts for groundwater management and regulation, but their nature and scope vary widely, and their implementation is inferior and ineffective. There is utter confusion about the custodian of this common property resource. Constitution says that water is a state subject while National Water Policy recognizes it as a national resource. The Environmental Protection Act of 1986 also covers water. Another central act, The Indian Easement Act, 1882, gives ownership of groundwater to the landowner. Now, this is the right time to recognize water as a national resource by law and enact a comprehensive central law to effectively control and manage it.

11. By 2050, India’s water demand will be 1180 BCM while the present total utilizable water is only1122BCM [35]. When the reliable source of fresh water supply, rainfall, has started reducing, becoming erratic, unpredictable, and unreliable while our demand is growing, it becomes imperative to search for reliable alternative sources of water supply.

Wastewater may be one of such reliable and potential water sources as it is available round the year in the same quantity. Over several decades, Israel has already done it by building a national wastewater infrastructure to make use of wastewater, especially, for irrigation, and presently reuses 85% of its wastewater. It has developed an integratedwastewater facility through which wastewater is collected, treated, stored, and transportedthrough a network of pipelines to arid areas for irrigation [1,12]. Accurate and consolidated information regarding generated wastewater is not available for India. However, it is also true that India is a highly populous nation, has 481.98 million urban populations approximately, and generates large quantities of wastewater daily. Problematic states like Punjab, Haryana, and Uttar Pradesh have urban populations of 10.4 million, 8.84 million, and 58.3 million respectively [36-39]. The average consumption of freshwater is 135 to 150 liters per capita per day (lpcd). If we take daily per capita freshwater consumption as 135 liters, per capita wastewater generated is 90% or about 121 lpcd. For a population of 481.98 million, the amount of generated wastewater comes out to be 21286.64 million cubic meters (MCM) per year. It does not include wastewater generated from industries, generally 50 to 60% of domestic wastewater. So total wastewater generated will be around 32994.29 MCM or about 33 BCM, which is about 50% of the net annual groundwater recharge of a big state like Uttar Pradesh and 8.3% of the country's net annual groundwater recharge [12, 24]. It is a sizeable quantity and in case of drought or monsoon failure, it may be the most reliable and perineal source of water supply to meet the demand. The strongest side of it is that it is available round the year in the same quantity. In the future, it will increase with an increasing population. Re-use is an essential adaptation method to tackle the high risk of reduced water availability through the effects of climate change. Presently only in urban areas, 72368 MLD (million liters per day) of sewage is produced of which only 26869 MLD is treated [35] and after treatment; the treated water is flown into the rivers. It is not reused. For reuse, it is to be further filtered, stored, and transported to needy areas. Thus, it is now the right time to develop integrated facilities to retrieve, treat, filter, and store and transport wastewater to meet the irrigation demand of needy areas and reduce pressure on groundwater. It requires a new vision, new investment, new skills, and new commitments.

12. To meet the emergencies caused by climate change, static groundwater resources and their quality also need to be estimated properly, and accordingly, infrastructure to harness this water resource needs to be developed.

13. Climate change is a reality now. To mitigate climate change, crop varieties, tolerant to increasing temperature and requiring less water with more productivity are to be developed and grown.

14. Adaptation is another time-tested way to reduce pressure on natural resources like water. It relates to our behaviors i.e. what we eat, how we live, what we wear, how we travel, how we make houses, how we do things, etc. For example, the habit of eating meat is not compatible with climate as producing one kilogram of meat requires far more water than producing one kilogram of millet. The same is the case with wheat and rice. So, we will have to change our eating habits to adapt the climate change and reduce the cropping area under sugarcane, wheat, and rice. Similarly, the present culture of making high-rise buildings is not compatible with climate as the energy required to build and operate these buildings is very high and air conditioners essentially used in these buildings release greenhouse gas. The construction of these buildings also causes land subsidence due to excessive withdrawal of groundwater. They also increase the ambient temperature around the building. Population control may be another effective way of adaptation as it will reduce pressure on the earth`s natural resources and save our beautiful green planet. Already we are harnessing natural resources which are two and half times more than the capacity of the earth to give if it is to remain sustainable.

Conclusion

The present paper argues that the pattern of rainfall is shifting in India and in the northwest and northcentral regions the rainfall is declining. These regions are very poorly forested and witness significant negative deviations in rainfall. Paper further argues that despite no significant change in overall rainfall, annual groundwater recharge, and annual groundwater draft of the country since 2004, numbers of problematic blocks (over-exploited, critical, and semi-critical blocks) rose continuously, indicating groundwater depletion and discrepancies in groundwater assessment methodology and norms. Increasing forest cover by 20% in next 25 years to mitigate extreme negative deviations in rainfall due to climate change and restricting area under water-guzzling crops in states like Punjab, Haryana, and Uttar Pradesh, promoting large scale community sprinkler schemes using existing tube wells and wells and community drip irrigation schemes like Horticulture Parks, improving irrigation and agriculture resource efficiency through automation, starting land subsidence survey followed by groundwater abstraction control and injection of water into aquifers in metropolitan cities, review of the policy of vertical development, revisiting groundwater assessment methodology and norms, improving surface and groundwater supplies through redevelopment and renovation of all the traditional large (> 1 hectare) water bodies to develop them as water sanctuaries, enacting comprehensive central groundwater law, creating the integrated facilities to retrieve, treat, filter, store and transport wastewater to the parched regions as an alternative source of water, transferring surplus groundwater from waterlogged areas to adjacent scarce areas, developing heat-tolerant crop varieties requiring less water, changing lifestyle and controlling population may contribute significantly towards effective solution to avert the future water crisis caused by climate change and restore groundwater.

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Author's contribution

The concept and design of the manuscript were prepared by all the authors. Data collection was also done jointly. The first draft of the manuscript was prepared by author Pratik Ranjan Chaurasia and the final draft was approved by all the authors.

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