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Energy consumption and CO_2 emission through groundwater abstraction in parts of gangetic alluvial plains of India

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Abstract
Water is not only an essential element for our survival but is also an important vehicle for economic development of any nation. Groundwater meets nearly 55% irrigation, 85% of rural and 50% of urban and industrial needs. Pumping groundwater for irrigation is the main energy consumption activity in agriculture in India. As small and marginal farmers dominate in agriculture sector, farm mechanisation is limited and groundwater abstraction becames the highest energy consuming process. Mostly diesel and electric pumps are used for abstraction that emits carbon dioxide a major component of green house gases which is of concern. To meet the increasing demand for water further abstraction of groundwater from declined water tables is inevitable. Farmers have been pumping ground water for successful crop production which demands higher energy consumption. Energy consumption and green house gas emission are the important concerns of any developing country. In the present study energy consumption and carbon emission through groundwater abstraction in different districts of Bihar state was studied. The impact of different water management options on the total annual groundwater draft, energy consumption and carbon emission was studied. Different water management scenarios were considered for energy conservation and carbon emission reduction. The different water management scenarios considered included:1. If 5- 20% of total tubewell irrigated area is converted into sprinkler irrigation system.2. If 5-20% of total tubewell irrigated area is converted into drip irrigation system. 3. If 10% combination of tubewell irrigated area comes under drip irrigation system and 10% under sprinkler irrigation system and remaining 80% under conventional irrigation system. The total energy requirement for pumping of groundwater from different irrigation structures in Bihar state was found to be 6672233 MWh. The highest energy requirement for groundwater pumping was found to be 770108 MWh for Patna district and lowest 22787 MWh for Banka district. The total CO_2 emission from pumping of ground water for the whole state was found to be 2276732 tonnes. Patna contributes highest and Banka contributes lowest carbon emission. The reduction in the total energy requirement and carbon emission from ground water pumping under water management options of case-1(a), case-1(b), case 1 (c) and case 1(d) were 2.5%, 5%, 7.5% and 10% respectively. The total carbon emission reduction under water management options case-2(a), case-2(b), case-2(c) and case-2(d) were 3%, 6%, 9% and 12%. The total reduction in energy requirement and carbon emission from ground water pumping under water management option case-3 was 11%. The water management option which includes combination of sprinkler, drip and conventional irrigation seems to the most suitable and feasible alternative for Bihar state.

Keywords: Carbon emission, sprinkler irrigation, drip irrigation, ground water

1. Introduction
Groundwater has rapidly emerged to occupy a dominant place in India's agriculture and food security in the recent years. It has become the main source of growth in irrigated area over the past 3 decades, and it now accounts for over 60 percent of the irrigated area in the country. It is estimated that now over 70 percent of India's food grain production comes from irrigated agriculture, in which groundwater plays a major role. Rainwater is the main source of water for agriculture in India but its current use efficiency for crop production is quite low (30-45%). Irrigated agriculture is essential to increase crop production to meet the increased food requirement in increasing population of India.
Pumping groundwater for irrigation is the main energy consumption activity in agriculture in India. As small and marginal farmers dominate in agriculture sector, farm mechanisation is little restricted and groundwater abstraction became the highest energy consuming process. Mostly diesel and electric pumps are used for abstraction that emits carbon dioxide a major component of green house gases which is of concern. With increasing demand for groundwater increase in the emission of green house gases for further abstraction of groundwater from declined water tables are inevitable.

Water use efficiency in the case of surface irrigation is substantially low compared to pressurised irrigation system such as sprinkler and drip. Pressurised irrigation system using groundwater as source could reduce energy consumption by 12-44%. Numerous field studies shows that the use of drip irrigation reduces the quantity of groundwater pumped / ha by 30-70% over surface irrigation depending upon the crop and season.

A planned approach including assessment of available water resources (surface and groundwater), crop planning based on crop water requirement is therefore essential for sustainable development of this precious natural resource as dependence on groundwater is likely to increase in future. Energy consumption and green house gas emission are one of the important concern of the developing economy of eastern Indo gangetic plain. Keeping the above facts in mind the present study was undertaken with following specific objectives:-

- To estimate the total energy consumption in groundwater abstraction in different districts of Bihar.
- To estimate carbon emission due to groundwater abstraction in different districts of Bihar.
- To study the impact of different water management options on total annual groundwater draft, energy consumption and carbon emission.

2. Materials and Methodology

The materials and methods which were adopted in this study are presented in the following subsections.

2.1 General Description of Study Area

Bihar is bounded by Uttar Pradesh to its west, Nepal to the north, West Bengal to the east and by Jharkhand to the south (Fig.1). Bihar is located in the eastern region of India between latitude 24°-20'-10" N ~ 27°-31'-15" N and longitude 82°-19'-50" E ~ 88°-17'-40" E. It is an entirely land–locked state, in a Sub Tropical region of the Temperate zone. Bihar lies mid between the humid West Bengal in the east and the sub humid Uttar Pradesh in the west which provides it with a transitional position in respect of climate, economy and culture. It is bounded by Nepal in the north and by Jharkhand in the south. Bihar plain is divided into two unequal halves (North Bihar and South Bihar) by the river Ganges which flows through the middle from west to east. Bihar is in Indo-Gangetic plain so naturally fertile soil is one asset of the state. Thus Indo-Gangetic plain's soil is the backbone of agricultural and industrial development. The Indo-Gangetic plain in Bihar consists of a thick alluvial mantle of drift origin overlying in most part. The siwalik and older tertiary rocks. The soil is mainly young loam rejuvenated every year by constant deposition of silt, clay and sand brought by streams but mainly by floods in Bihar. Bihar's land has average elevation above sea level is 173 feet.

Fig 1: Geographical map of Bihar state

2.2 Estimation of Annual Draft (ha-m)

The amount of ground water extracted from the ground resources with the help of pumping unit is called ground water draft. The groundwater draft was calculated by using the norms of GEC-1997 [1] using unit draft as 0.6, 1.0, and 30.0 ha m for dug wells, shallow tube wells and deep tube wells, respectively. The annual draft is calculated by multiplying number of tube wells and unit draft.

2.3 Estimation of Energy (KWh)

The energy required for groundwater abstraction will be estimated as per the methodology provided by Rothausen and Conway, 2011 [4] which prescribes the energy required to lift $1m^3$ of water (with a density 1000 kg-m^3) up 1m at 100% efficiency is 0.0027 KWh (1),

$$\text{Energy (KWh)} = \frac{9.8ms^{-2} * lift(m) * mass(kg)}{3.6 * 10^6 * efficiency(\%)} \qquad (1)$$

In practice, the efficiency of this process is closer to 20 to 30 percent of theoretical maximum. Here 30 percent efficiency rate has been considered, the effective energy use in 9.080 KWh per thousand cubic meters of water lifted one meter vertically. All the district of Bihar selected for study and the standard lift for dugwells, shallow tube wells and deep tube wells are 15, 30 and 80 m respectively.

2.4 Estimation of Carbon Emission

The amount of CO_2 released to lift 1000 m^3 of water one meter depends on source of energy. Diesel does not have a unique chemical formulation so the mass and carbon vary by mixture. A litre of standard diesel fuel contains approximately 0.732 kg carbon, a mass of approximately 0.85 kg and an energy content of approximately 10.01 kWh. So with diesel pump the amount of carbon released to lift 1000 m^3 of water one meter is 0.665 kg C (0.732*9.080/10.01). The ratio of carbon emission to energy content for diesel is 0.0732 kg C per kWh (Nelson and Robertson, 2008) [2].

The all India average value of 1.4894 kg of CO_2 per kWh at the station (0.4062 kg C per kWh) was used to estimate the release of CO_2 from electric pumps. With five percent transmission losses an effective carbon emission rate of 0.4265 kg C per kWh at the generating facility or 3.873 kg C to lift 1000 m^3 upto one meter was used. The emission from coal based electricity is about 5.82 (3.873/0.665) times higher than the rate of emission with diesel pumps (Nelson *et al.*, 2009) [3].

2.5 Water Management Option for Energy Consumption and Carbon Emission Reduction

Different water management scenarios were considered for energy conservation and carbon emission reduction. The following water management scenarios were considered.

Case-1

(a) If 5% of total tubewell irrigated area is converted into sprinkler irrigation system.
(b) If 10% of total tubewell irrigated area is converted into sprinkler irrigation system.
(c) If 15% of total tubewell irrigated area is converted into sprinkler irrigation system.
(d) If 20% of total tubewell irrigated area is converted into sprinkler irrigation system.

Case-2

(a) If 5% of total tubewell irrigated area is converted into drip irrigation system.
(b) If 10% of total tubewell irrigated area is converted in to drip irrigation system.
(c) If 15% of total tubewell irrigated area is converted in to drip irrigation system.
(d) If 20% of total tubewell irrigated area is converted in to drip irrigation system.

Case-3

(a) If 10% combination of tubewell irrigated area comes under drip irrigation system, 10% under sprinkler irrigation system and remaining 80% under conventional irrigation system.

3. Results and Discussion

3.1 Energy (kWh) Requirement for Pumping of Groundwater from Different Irrigation Structures

Groundwater irrigation is mostly practised by the farmers in this part of the country. The total energy requirement for pumping of groundwater from different irrigation structures was found to be 6672233 MWh. The total energy requirement for dug well, shallow tube well and for deep tube well were found to be 45855 MWh, 1557777 MWh and 5068601 MWh respectively (Table 1).The highest energy requirement for groundwater pumping was found to be 770109 MWh for Patna district and lowest 22787 MWh for Banka district.

3.2 CO_2 Emission (in tonne) from Groundwater Pumping

The emission of CO_2 was estimated for different districts using different irrigation structures driven by diesel or electricity and presented in table 2. The total CO_2 emission from pumping of groundwater for the whole state was found to be 2276732 tonne. The data revealed that the Patna contributes highest followed by Rohtas and Begusarai. It was observed that more the number of deep tube wells more amount of carbon emitted. Patna has the highest number of deep tube well followed by Rohtas and Begusarai. The above said districts are intensively cultivated mostly those crops for which higher amount of groundwater is drafted and the higher amount of groundwater is drafted through deep tube well using electric pumps. The lowest CO_2 emission was found in Banka district. The groundwater development in hilly districts like Banka, Kishanganj, Jamui etc. of Bihar were found to be difficult and costly because of hard rock formation.

Table 1: Energy (kWh) requirement for pumping of groundwater from different irrigation structures

S. No.	Name of districts	dug wells	shallow tube wells	deep tube wells	Total
1	Araria	64559	18090084	9152640	27307283
2	Aurangabad	2984414	20598888	239276160	262859462
3	Banka	2364977	13884228	6537600	22786805
4	Begusarai	417589	33341760	437147520	470906869
5	Kaimur	4983286	35967696	76489920	117440902
6	Bhagalpur	92344	31838112	5883840	37814296
7	Bhojpur	1201284	58980048	120509760	180691092
8	Buxar	1161241	45613380	121381440	168156061
9	East Champaran	446191	71347008	67555200	139348399
10	West Chamaran	49032	44956896	24624960	69630888
11	Darbhanga	94795	28789956	19830720	48715471
12	Gaya	4701352	88712508	80412480	173826340
13	Gopalganj	1951474	59791800	81937920	143681194
14	Jamui	4915458	4442844	125521920	134880222
15	Jehanabad	158537	55019352	132277440	187455329
16	Katihar	76000	66353916	94577280	161007196
17	Khagaria	345676	17199336	192641280	210186292
18	Kishhanganj	19613	18574956	9588480	28183049
19	Lakhisarai	222278	16692672	53390400	70305350
20	Madhepura	109505	34532148	14818560	49460213
21	Madhubani	205934	46923624	88693440	135822998

22	Munger	1862399	14110320	205062720	221035439
23	Muzaffarpur	170795	95299140	32034240	127504175
24	Nalanda	7561552	67301868	252569280	327432700
25	Nawada	1777410	34720104	414483840	450981354
26	Patna	2602782	64060308	703445760	770108850
27	Purnia	80086	63224040	220970880	284275006
28	Rohtas	997801	24336216	538698240	564032257
29	Sasaram	53118	14480784	97628160	112162062
30	Samstipur	116042	84580200	154069440	238765682
31	Saran	1041113	75462972	115061760	191565845
32	Shekhpura	159354	10029768	51864960	62054082
33	Sheohar	213289	9863604	23099520	33176413
34	Sitamarhi	188773	27299928	51647040	79135741
35	Siwan	1600078	65662020	173028480	240290578
36	Supaul	28602	25341372	14600640	39970614
37	Vaisali	835996	70352748	18087360	89276104
Total		45854726	1557776604	5068601280	6672232610

Table 2: Carbon emission (in tonne) for pumping of groundwater from different irrigation structures

Sl. No.	Name of districts	dug wells	shallow tube wells	deep tube wells	Total
1	Araria	5	1324	3899	5228
2	Aurangabad	218	1508	101937	103664
3	Banka	173	1016	2785	3975
4	Begusarai	31	2441	186235	188707
5	Kaimur	365	2633	32587	35584
6	Bhagalpur	7	2331	2507	4844
7	Bhojpur	88	4317	51340	55745
8	Buxar	85	3339	51711	55135
9	East Champaran	33	5223	28780	34035
10	West Chamaran	4	3291	10491	13785
11	Darbhanga	7	2107	8448	10563
12	Gaya	344	6494	34258	41096
13	Gopalganj	143	4377	34908	39427
14	Jamui	360	325	53475	54160
15	Jehanabad	12	4027	56353	60392
16	Katihar	6	4857	40292	45155
17	Khagaria	25	1259	82070	83354
18	Kishhanganj	1	1360	4085	5446
19	Lakhisarai	16	1222	22746	23984
20	Madhepura	8	2528	6313	8849
21	Madhubani	15	3435	37786	41235
22	Munger	136	1033	87362	88531
23	Muzaffarpur	13	6976	13647	20636
24	Nalanda	554	4926	107601	113081
25	Nawada	130	2542	176580	179252
26	Patna	191	4689	299685	304565
27	Purnia	6	4628	94139	98773
28	Rohtas	73	1781	229498	231353
29	Sasaram	4	1060	41592	42656
30	Samstipur	8	6191	65637	71837
31	Saran	76	5524	49019	54619
32	Shekhpura	12	734	22096	22842
33	Sheohar	16	722	9841	10579
34	Sitamarhi	14	1998	22003	24015
35	Siwan	117	4806	73714	78638
36	Supaul	2	1855	6220	8077
37	Vaisali	61	5150	7706	12917
Total		3357	114029	2159346	2276732

3.3 Water Management Option for Energy and CO_2 Reduction in Groundwater Pumping

3.3.1 If 5% of tube well irrigated area comes under sprinkler irrigation system [case-1(a)]

Table 3 shows the total energy requirement under water management option of converting 5% of total tube well irrigated area under sprinkler irrigation system. The total energy requirement and carbon emission under this water management option reduced by 2.5%. The total energy requirement for whole state for groundwater pumping was found to be 6505427 MWh. The CO_2 emission for the whole state was found to be 2219813 tonnes (table 4).

3.3.2 If 10% of tube well irrigated area comes under sprinkler irrigation system [case-1(b)]

The reduction in total energy requirement and carbon emission under water management option case-1(b) was 5%.The total energy requirement under option case-1(b) for groundwater pumping for Bihar state was found to be 6338621 MWh (table 3). The total carbon emission under this case was found to be 2162895 tonnes (table 4). The energy saved under this water management option can be used for further development of groundwater.

3.3.3 If 15% of tube well irrigated area comes under sprinkler irrigation [case-1(c)]

Table 3 displays energy (kWh) requirement under water management option case-1(c). The total energy requirement for pumping of groundwater under the scenario case-1(c) was 6171815 MWh (table 3). The total energy requirement reduced by 7.5%. When similar comparison was made for carbon emission under water management option case-1(c) it was 2105977 tonnes (table 4).

3.3.4 If 20% of tube well irrigated area comes under sprinkler irrigation [case-1(d)]

The total energy requirement under the water management option case 1(d) was 6005009 MWh (table 3). The total energy requirement and carbon emission reduced by 10%, when comparison was made with current situation. The total carbon emission under this option was found to be 2049058 tonnes (table 4). The crops like wheat, rice, pulses and maize etc. can be easily irrigated with sprinkler irrigation system with high water use efficiency. The energy saved under this water management option can be used for further development of groundwater.

Table 3: Energy (kWh) requirement for pumping of groundwater under different water management options Case 1(a) to case 1(d)

S. No.	Name of district	Control	Case 1 (a)	Case 1(b)	Case 1(c)	Case 1 (d)
1	Araria	27307283	26624601	25941919	25259237	24576555
2	Aurangabad	262859462	256287976	249716489	243145003	236573516
3	Banka	22786805	22217135	21647465	21077794	20508124
4	Begusarai	470906869	459134197	447361526	435588854	423816182
5	Kaimur	117440902	114504879	111568857	108632834	105696811
6	Bhagalpur	37814296	36868938	35923581	34978223	34032866
7	Bhojpur	180691092	176173815	171656537	167139260	162621983
8	Buxar	168156061	163952160	159748258	155544357	151340455
9	EastChamparan	139348399	135864689	132380979	128897269	125413559
10	WestChamaran	69630888	67890116	66149344	64408571	62667799
11	Darbhanga	48715471	47497584	46279698	45061811	43843924
12	Gaya	173826340	169480681	165135023	160789364	156443706
13	Gopalganj	143681194	140089164	136497134	132905104	129313074
14	Jamui	134880222	131508216	128136211	124764205	121392200
15	Jehanabad	187455329	182768946	178082562	173396179	168709796
16	Katihar	161007196	156982016	152956836	148931656	144906476
17	Khagaria	210186292	204931634	199676977	194422320	189167662
18	Kishhanganj	28183049	27478473	26773896	26069320	25364744
19	Lakhisarai	70305350	68547717	66790083	65032449	63274815
20	Madhepura	49460213	48223707	46987202	45750697	44514192
21	Madhubani	135822998	132427423	129031848	125636274	122240699
22	Munger	221035439	215509553	209983667	204457781	198931895
23	Muzaffarpur	127504175	124316570	121128966	117941362	114753757
24	Nalanda	327432700	319246882	311061065	302875247	294689430
25	Nawada	450981354	439706820	428432286	417157752	405883219
26	Patna	770108850	750856129	731603408	712350686	693097965
27	Purnia	284275006	277168130	270061255	262954380	255847505
28	Rohtas	564032257	549931451	535830644	521729838	507629031
29	Sasaram	112162062	109358010	106553959	103749907	100945856
30	Samstipur	238765682	232796540	226827398	220858256	214889114
31	Saran	191565845	186776699	181987553	177198406	172409260
32	Shekhpura	62054082	60502730	58951378	57400026	55848674
33	Sheohar	33176413	32347003	31517593	30688182	29858772
34	Sitamarhi	79135741	77157348	75178954	73200561	71222167
35	Siwan	240290578	234283313	228276049	222268784	216261520
36	Supaul	39970614	38971349	37972083	36972818	35973553
37	Vaishali	89276104	87044201	84812298	82580396	80348493
Total		6672232610	6505426795	6338620980	6171815165	6005009349

Table 4: Carbon emission (in tonne) for pumping of groundwater different water management options Case 1(a) to case 1(d)

S. N	Name of district	Control	Case 1 (a)	Case 1(b)	Case 1(c)	Case 1 (d)
1	Araria	5228	5097	4967	4836	4705
2	Aurangabad	103664	101072	98481	95889	93297
3	Banka	3975	3875	3776	3677	3577
4	Begusarai	188707	183989	179271	174554	169836
5	Kaimur	35584	34695	33805	32915	32026
6	Bhagalpur	4844	4723	4602	4481	4360
7	Bhojpur	55745	54352	52958	51564	50171
8	Buxar	55135	53757	52379	51000	49622

9	EastChamparan	34035	33185	32334	31483	30632
10	WestChamaran	13785	13441	13096	12751	12407
11	Darbhanga	10563	10299	10035	9771	9506
12	Gaya	41096	40068	39041	38013	36986
13	Gopalganj	39427	38441	37456	36470	35484
14	Jamui	54160	52806	51452	50098	48744
15	Jehanabad	60392	58883	57373	55863	54353
16	Katihar	45155	44026	42897	41768	40639
17	Khagaria	83354	81270	79186	77103	75019
18	Kishhanganj	5446	5310	5174	5038	4901
19	Lakhisarai	23984	23384	22785	22185	21585
20	Madhepura	8849	8628	8406	8185	7964
21	Madhubani	41235	40205	39174	38143	37112
22	Munger	88531	86318	84104	81891	79678
23	Muzaffarpur	20636	20120	19604	19088	18572
24	Nalanda	113081	110254	107427	104600	101773
25	Nawada	179252	174770	170289	165808	161327
26	Patna	304565	296950	289336	281722	274108
27	Purnia	98773	96303	93834	91365	88895
28	Rohtas	231353	225569	219785	214001	208218
29	Sasaram	42656	41589	40523	39457	38390
30	Samstipur	71837	70041	68245	66449	64653
31	Saran	54619	53254	51888	50523	49157
32	Shekhpura	22842	22271	21699	21128	20557
33	Sheohar	10579	10314	10050	9785	9521
34	Sitamarhi	24015	23415	22814	22214	21614
35	Siwan	78638	76672	74706	72740	70774
36	Supaul	8077	7875	7673	7472	7270
37	Vaishali	12917	12594	12271	11948	11625
Total		2276732	2276732	2162895	2105977	2049058

3.3.5 If 5% of tube well irrigated area comes under drip irrigation [case-2(a)]

Drip irrigation is most efficient irrigation system developed so far. Under this scenario 5% of tube well irrigated area is converted into drip irrigation system. The analysis revealed that the total energy requirement is reduced by 3%. Under this scenario the total energy requirement was 6472066 MWh (Table 5), where as the total carbon emission was 2208430 tonnes (Table 6). The total carbon emission also reduced by 3% compared to current situation.

3.3.6 If 10% of tube well irrigated area comes under sprinkler irrigation [case-2(b)]

The energy requirement and carbon emission reduced by 6% under this water management option. The total energy requirement for ground water under this water management option was 6271899 MWh (Table 5) where as carbon emission was 2140128 tonnes (table 6).

3.3.7 If 15% of tube well irrigated area comes under drip irrigation [case-2(c)]

The energy requirement and carbon emission reduced by 9% under this water management option. The total energy requirements for pumping of groundwater from different irrigation structures were 6071732 MWh (Table 5).

3.3.8 If 20% of tube well irrigated area comes under drip irrigation[case-2(d)]

The energy requirement and carbon emission reduced by 12% under this water management option. The total energy requirement for ground water under this water management option was 5871565 MWh (Table 5) where as carbon emission was 2003524 tonnes (Table 6).

3.3.9 If 10% of tube well irrigated area comes under drip irrigation, 10% area comes under sprinkler irrigation and remaining 80% under conventional irrigation [case- 3]

The total energy requirement of under water management option case (3) for pumping of groundwater from different irrigation structures were 5938287 MWh (table7). The total energy requirement and carbon emission reduced by11% under case-3 water management option. The total carbon emission under water management option case-3 was found to be 2026291tonnes (table 7). Based on the analysis this water management option seems to be best suitable for the state. Practically, it is the most feasible option because drip irrigation is suited for vegetable & horticultural crops and sprinkler irrigation is suited for wheat, pulses etc. The combination of sprinkler and drip irrigation can be one of the best alternatives.

Table 5: Energy (kWh) requirement for pumping of groundwater under different water management options case 2(a) to case 2(d)

S. N	Name of district	Control	Case 2 (a)	Case 2 (b)	Case 2(c)	Case 2 (d)
1	Araria	27307283	26488064	25668846	24849627	24030409
2	Aurangabad	262859462	254973679	247087895	239202111	231316327
3	Banka	22786805	22103201	21419597	20735992	20052388
4	Begusarai	470906869	456779663	442652457	428525251	414398045
5	Kaimur	117440902	113917675	110394448	106871220	103347993
6	Bhagalpur	37814296	36679867	35545438	34411009	33276580
7	Bhojpur	180691092	175270359	169849626	164428894	159008161
8	Buxar	168156061	163111379	158066698	153022016	147977334

9	EastChamparan	139348399	135167947	130987495	126807043	122626591
10	WestChamaran	69630888	67541961	65453035	63364108	61275181
11	Darbhanga	48715471	47254007	45792543	44331079	42869615
12	Gaya	173826340	168611549	163396759	158181969	152967179
13	Gopalganj	143681194	139370758	135060322	130749886	126439450
14	Jamui	134880222	130833815	126787409	122741002	118694595
15	Jehanabad	187455329	181831669	176208009	170584349	164960689
16	Katihar	161007196	156176980	151346764	146516548	141686332
17	Khagaria	210186292	203880703	197575114	191269525	184963937
18	Kishhanganj	28183049	27337557	26492066	25646574	24801083
19	Lakhisarai	70305350	68196190	66087029	63977869	61868708
20	Madhepura	49460213	47976406	46492600	45008794	43524987
21	Madhubani	135822998	131748308	127673618	123598929	119524239
22	Munger	221035439	214404376	207773312	201142249	194511186
23	Muzaffarpur	127504175	123679050	119853924	116028799	112203674
24	Nalanda	327432700	317609719	307786738	297963757	288140776
25	Nawada	450981354	437451913	423922473	410393032	396863592
26	Patna	770108850	747005585	723902319	700799054	677695788
27	Purnia	284275006	275746755	267218505	258690255	250162005
28	Rohtas	564032257	547111289	530190322	513269354	496348386
29	Sasaram	112162062	108797200	105432338	102067476	98702615
30	Samstipur	238765682	231602712	224439741	217276771	210113801
31	Saran	191565845	185818869	180071894	174324919	168577943
32	Shekhpura	62054082	60192460	58330837	56469215	54607592
33	Sheohar	33176413	32181121	31185828	30190536	29195244
34	Sitamarhi	79135741	76761669	74387597	72013524	69639452
35	Siwan	240290578	233081860	225873143	218664426	211455708
36	Supaul	39970614	38771496	37572377	36373259	35174140
37	Vaishali	89276104	86597820	83919537	81241254	78562971
Total		6672232610	6472065632	6271898654	6071731675	5871564697

Table 6: Carbon emission (in tonne) for pumping of groundwater different water management options case 2(a) to case 2(d)

S. N	Name of district	Control	Case 2 (a)	Case 2(b)	Case 2 (c)	Case 2 (d)
1	Araria	5228	5071	4914	4758	4705
2	Aurangabad	103664	100554	97444	94334	93297
3	Banka	3975	3855	3736	3617	3577
4	Begusarai	188707	183045	177384	171723	169836
5	Kaimur	35584	34517	33449	32382	32026
6	Bhagalpur	4844	4699	4553	4408	4360
7	Bhojpur	55745	54073	52401	50728	50171
8	Buxar	55135	53481	51827	50173	49622
9	EastChamparan	34035	33014	31993	30972	30632
10	WestChamaran	13785	13372	12958	12545	12407
11	Darbhanga	10563	10246	9929	9612	9506
12	Gaya	41096	39863	38630	37397	36986
13	Gopalganj	39427	38244	37062	35879	35484
14	Jamui	54160	52536	50911	49286	48744
15	Jehanabad	60392	58581	56769	54957	54353
16	Katihar	45155	43800	42446	41091	40639
17	Khagaria	83354	80853	78353	75852	75019
18	Kishhanganj	5446	5283	5119	4956	4901
19	Lakhisarai	23984	23264	22545	21825	21585
20	Madhepura	8849	8583	8318	8052	7964
21	Madhubani	41235	39998	38761	37524	37112
22	Munger	88531	85875	83219	80563	79678
23	Muzaffarpur	20636	20017	19398	18779	18572
24	Nalanda	113081	109688	106296	102903	101773
25	Nawada	179252	173874	168497	163119	161327
26	Patna	304565	295428	286291	277154	274108
27	Purnia	98773	95810	92846	89883	88895
28	Rohtas	231353	224412	217472	210531	208218
29	Sasaram	42656	41376	40096	38817	38390
30	Samstipur	71837	69682	67527	65372	64653
31	Saran	54619	52981	51342	49703	49157
32	Shekhpura	22842	22156	21471	20786	20557
33	Sheohar	10579	10261	9944	9627	9521
34	Sitamarhi	24015	23295	22574	21854	21614
35	Siwan	78638	76279	73920	71560	70774
36	Supaul	8077	7835	7593	7350	7270
37	Vaishali	12917	12529	12142	11754	11625
Total		2276732	2208430	2140128	2071826	2003524

Table 7: Energy (kWh) requirement and carbon emission (tonne) under case-3 water management option for pumping of groundwater

S. No.	Name of district	Control (Energy Req.)	Case 3 (a) (Energy Req.)	Control (Carbon Emiss.)	Case 3 (a) (Carbon Emiss.)
1	Araria	27307283	24303482	5228	4653
2	Aurangabad	262859462	233944922	103664	92261
3	Banka	22786805	20280256	3975	3537
4	Begusarai	470906869	419107114	188707	167949
5	Kaimur	117440902	104522402	35584	31670
6	Bhagalpur	37814296	33654723	4844	4311
7	Bhojpur	180691092	160815072	55745	49613
8	Buxar	168156061	149658894	55135	49070
9	EastChamparan	139348399	124020075	34035	30292
10	West Chamaran	69630888	61971490	13785	12269
11	Darbhanga	48715471	43356769	10563	9401
12	Gaya	173826340	154705442	41096	36575
13	Gopalganj	143681194	127876262	39427	35090
14	Jamui	134880222	120043398	54160	48203
15	Jehanabad	187455329	166835243	60392	53749
16	Katihar	161007196	143296404	45155	40188
17	Khagaria	210186292	187065800	83354	74185
18	Kishhanganj	28183049	25082913	5446	4847
19	Lakhisarai	70305350	62571762	23984	21346
20	Madhepura	49460213	44019589	8849	7875
21	Madhubani	135822998	120882469	41235	36700
22	Munger	221035439	196721541	88531	78792
23	Muzaffarpur	127504175	113478716	20636	18366
24	Nalanda	327432700	291415103	113081	100642
25	Nawada	450981354	401373405	179252	159534
26	Patna	770108850	685396877	304565	271062
27	Purnia	284275006	253004755	98773	87908
28	Rohtas	564032257	501988709	231353	205904
29	Sasaram	112162062	99824235	42656	37964
30	Samstipur	238765682	212501457	71837	63935
31	Saran	191565845	170493602	54619	48611
32	Shekhpura	62054082	55228133	22842	20329
33	Sheohar	33176413	29527008	10579	9415
34	Sitamarhi	79135741	70430810	24015	21373
35	Siwan	240290578	213858614	78638	69988
36	Supaul	39970614	35573846	8077	7189
37	Vaishali	89276104	79455732	12917	11496
Total		6672232610	5938287023	2276732	2026291

Conclusions

Ground water pumping is one of the major user of energy in agriculture and is one of major contributor of carbon emission in agriculture. It may be concluded from the above study that the places where deep tube wells are used for irrigation using electric pumps contribute more towards Green House Gas emission. On the other hand use of dug wells and shallow tube wells using diesel pumps are more environment friendly. Drip irrigation is the most effective water management option for energy requirement and carbon emission reduction. The water management option which includes combination of sprinkler, drip and conventional irrigation seems to the most suitable and feasible alternative for Bihar state. Renewable sources of energy like, solar, wind and biofuels may be encouraged to reduce carbon dioxide emissions.

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