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Effects of Water Source Quality on Steam Generation in a Rice Processing Plant: A Laboratory Study using a Marcet Boiler

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ABSTRACT
Steam is essential in rice processing, yet many plants in developing countries raise it from untreated water, and the effect of the water source on the time and energy needed is rarely quantified. This study compared three feed water sources in Makurdi, Nigeria: surface water (River Benue), groundwater (borehole) and rainwater. Samples were collected monthly from April to June, and thirteen physico-chemical parameters were determined using standard methods (APHA/AWWA/WEF). Each source was then used to generate steam in a Marcet boiler, recording pressure, temperature and elapsed time from 1 to 7 bar. Surface water had the highest colour (1538 Pt-Co), turbidity (359 NTU) and suspended solids (177 mg/l). Groundwater had the highest dissolved solids (899 mg/l), alkalinity (1169 mg/l), hardness (126 mg/l) and calcium (50 mg/l). Rainwater was the cleanest source on most parameters (TDS 68 mg/l; alkalinity 19 mg/l). Rainwater reached 7 bar in 30 min 52 s, compared with 40 min 3 s for groundwater and 42 min 20 s for surface water. At a fixed heater rating this corresponds to about 30% and 37% more electrical energy, respectively. Feed water source therefore materially affects startup time and energy demand, and surface water solids and groundwater alkalinity call for treatment before use.

Keywords: Water Source; Feed Water Quality; Steam Generation; Marcet Boiler; Energy Consumption; Rice Processing

INTRODUCTION

Water is essential to industry, yet natural water is never pure: as it falls as rain and passes over and through the ground it picks up dissolved and suspended impurities that decide how it can be used. In the United States, for example, industrial withdrawals are the fourth largest category of water use and come mostly from fresh surface water and groundwater, and the food and beverage sector is one of the industries that depend on treated water (Meese et al., 2022).

Steam is one of the largest industrial uses of both water and energy. About 30% of the energy consumed by the manufacturing industry is reported to be used to raise steam in industrial boilers (Demirel et al., 2021), and boiler efficiency depends on fuel quality, operating load and the quality of the feed water (Bashori and Subrianto, 2026). In rice processing, steam is used mainly for parboiling, which is an energy-intensive operation (Muchlisyiyah et al., 2023). In Makurdi, Benue State, rice processing plants draw on whatever water is locally available, namely River Benue, boreholes and harvested rainwater, often with little or no treatment, and plant records point to high energy use and long delays before steam is raised (MIKAP, 2020, 2021).

Feed-water impurities are a known cause of such losses. Inadequately treated feed water leads to scale formation and corrosion that shorten boiler life and raise maintenance costs (Shokri and Sanavi Fard, 2023), and mineral scale on heated surfaces increases the resistance to heat transfer and therefore the energy needed (Al-Gailani et al., 2021). In a fire-tube boiler operated under industrial conditions, feed-water hardness was strongly and negatively associated with thermal efficiency (Bashori and Subrianto, 2026), and in a survey of palm oil mills, total dissolved solids, silica, hardness and iron were the main factors affecting boiler-water treatment (Rusdi et al., 2022).

Studies of River Benue water at Makurdi have concentrated on its pollution status and ecological health (Otene et al., 2025), and harvested rainwater in Nigeria is usually assessed for domestic use (Nwachukwu et al., 2023). To our knowledge, the effect of the water source on steam generation in a Nigerian rice processing context has not been measured. This study therefore (i) characterised the physico-chemical quality of three water sources available in Makurdi (surface water, groundwater and rainwater); (ii) measured the pressure, temperature and time needed to generate steam from each source in a Marcet boiler; and (iii) related water quality to the energy demand and the boiler integrity risks associated with each source.

MATERIALS AND METHODS

Study Area and Sampling

The study was carried out in Makurdi, the capital of Benue State, north central, Nigeria (Fig. 1). Water was sampled from three sources: rainwater (trapped during rainfall), surface water (River Benue) and groundwater (the South Core borehole of Joseph Sarwuan Tarka University, Makurdi, formerly the University of Agriculture, Makurdi). Samples were collected according to standard laboratory procedures (APHA/AWWA/WEF, 2012) at monthly intervals over three months (April, May and June) in triplicate, giving 27 samples (3 sources × 3 months × 3 replicates). Monthly values are reported as the mean of the three replicates.

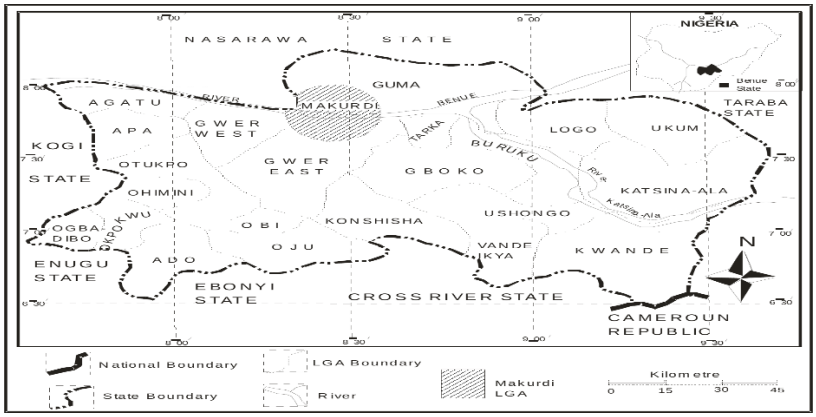

Figure 1: Map of Nigeria Showing Benue State and Makurdi, The Study Area. Source: BSMLS (2018)

Laboratory Analysis

Samples were transported to the laboratory of the Benue State Environmental Sanitation Authority (BENSESA), Makurdi, and analysed according to standard methods (APHA/AWWA/WEF, 2012). Five physical parameters (colour, temperature, turbidity, TDS and TSS) and eight chemical parameters (pH, electrical conductivity, total hardness, total alkalinity, nitrate, phosphate, calcium and magnesium) were determined with the instruments listed in Table 1.

Table 1: Parameters, Units and Methods or Instruments Used for Water Analysis

Parameter	Unit	Method / instrument
Colour	Pt-Co	Colorimetric
Temperature	°C	Glass-bulb thermometer
Turbidity	NTU	Turbidimeter
Total dissolved solids (TDS)	mg/l	TDS meter
Total suspended solids (TSS)	mg/l	Spectrophotometer
pH	–	pH meter
Electrical conductivity (EC)	µS/cm	Conductivity meter
Total hardness (TH)	mg/l as $CaCO_3$	Digital titrator
Total alkalinity (TA)	mg/l as $CaCO_3$	Digital titrator
Nitrate	mg/l	Spectrophotometer
Phosphate	mg/l	Titrimetric method
Calcium	mg/l	Titrimetric method
Magnesium	mg/l	Titrimetric method

Steam Generation Tests

Steam was generated in a Marcet boiler (SOLTEQ model HE169; Fig. 2), an electrically heated laboratory pressure vessel with a pressure transducer and Bourdon-tube gauge, a temperature sensor, a pressure relief valve and a water inlet port (SOLTEQ, 2011). For each test, a sample of one water source was introduced through the inlet port and heated until steam was produced. Pressure (bar), steam temperature (°C) and elapsed time (min:s) were recorded at 0.5-bar intervals from 1.0 to 7.0 bar. Tables 5 and 6 present one run per source. Energy consumption was estimated from the heating time and the heater rating stamped on the appliance, which is the maximum power the appliance draws (SOLTEQ, 2011). Because the same heater was used for all three sources, energy is proportional to heating time ($E = P \times t$), and the sources can be compared directly through their relative heating times and relative energy indices.

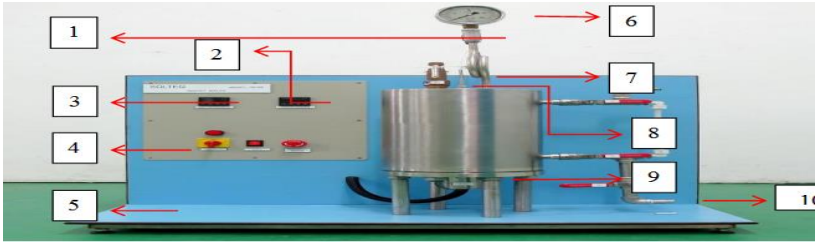

Figure. 2: Marcet Steam Boiler Used in The Experiment
Key: 1, Pressure Transducer; 2, Pressure Indicator; 3, Temperature Indicator/Controller; 4, Control Panel; 5, Bench; 6, Bourdon-Tube Pressure Gauge; 7, Temperature Sensor; 8, Pressure Relief Valve; 9, Heater; 10, Water Inlet Port and Valve. Adapted from SOLTEQ (2011)

Data Analysis

For each parameter, the three monthly means of each source were used to calculate the overall mean and standard deviation (SD) (n = 3). Differences among sources were tested by one-way analysis of variance (ANOVA) at the 5% significance level. Measured values were compared with the Nigerian standard for drinking water (NIS/SON, 2015), the national reference for the parameters considered, and the interpretation of each parameter for boiler use draws on the boiler water treatment literature (Shokri and Sanavi Fard, 2023; BSI, 1997). Steam temperatures were compared with saturation temperatures from standard steam tables.

RESULTS AND DISCUSSION

Water Quality of the Three Sources

The water quality results are presented in four steps: monthly means of the physical parameters (Table 2) and of the chemical parameters (Table 3), the three-month means with standard deviations, significance tests and drinking-water limits (Table 4), and the monthly trends of four key parameters (Fig. 3).

Table 2 gives the monthly means of the five physical parameters (colour, temperature, turbidity, TSS and TDS) for each source. Surface water was the most coloured source in every month, but its colour fell from 1723.0 Pt-Co in April to 1378.6 Pt-Co in June, whereas its turbidity peaked in May (412.0 NTU). Its TDS was lower in May (598.3 mg/l) than in April (868.3 mg/l) and June (878.6 mg/l), and its TSS was likewise lowest in May (115.3 mg/l, against 213.0 and 203.3 mg/l). Groundwater was stable over the three months, with colour of 33.0–43.3 Pt-Co, turbidity of 10.0–16.3 NTU and TDS of 826.3–938.6 mg/l. Rainwater had low and stable colour (26.6–31.3 Pt-Co), TSS (20.6–25.3 mg/l) and TDS (62.6–70.6 mg/l), and its temperature (22.6–24.0 °C) was lower than that of the other sources (28.0–30.6 °C). Its turbidity, however, declined from 103.0 NTU in April to 77.0 NTU in May and 10.6 NTU in June.

Table 2: Monthly Means of Physical Parameters of the Three Water Sources (April – June)

Source	Parameter	April	May	June
Surface water	Colour (Pt-Co)	1723.0	1513.3	1378.6
	Temperature (°C)	30.6	28.0	29.0
	Turbidity (NTU)	328.0	412.0	336.0
	TSS (mg/l)	213.0	115.3	203.3
	TDS (mg/l)	868.3	598.3	878.6
Groundwater	Colour (Pt-Co)	39.0	43.3	33.0
	Temperature (°C)	29.8	29.3	29.0
	Turbidity (NTU)	13.0	16.3	10.0
	TSS (mg/l)	44.6	49.0	38.0
	TDS (mg/l)	933.3	826.3	938.6
Rainwater	Colour (Pt-Co)	31.3	28.3	26.6
	Temperature (°C)	23.9	22.6	24.0
	Turbidity (NTU)	103.0	77.0	10.6
	TSS (mg/l)	25.3	21.6	20.6
	TDS (mg/l)	70.6	62.6	70.0

TSS: total suspended solids; TDS: total dissolved solids. Each value is the mean of three replicates.

Table 3 gives the monthly means of the eight chemical parameters. Groundwater had the highest total alkalinity (1095.0–1209.3 mg/l), total hardness (122.3–129.3 mg/l), calcium (48.60–51.00 mg/l), magnesium (1.36–1.44 mg/l) and nitrate (2.93–3.50 mg/l) in every month, and these values varied little between months. Its pH was 6.60, 6.80 and 6.00 in April, May and June, the June value being the lowest recorded in any source. In surface water, pH decreased from 8.20 in April to 7.90 in June, total alkalinity remained between 196.6 and 224.3 mg/l, hardness (9.0–14.3 mg/l) and calcium (4.16–4.73 mg/l) were low, and phosphate was the highest of the three sources in every month (0.41–0.66 mg/l). Electrical conductivity was similar in surface water (320.0–368.3 µS/cm) and groundwater (319.3–359.6 µS/cm).

Rainwater had the lowest value in every month for EC (8.0–10.5 µS/cm), total hardness (5.0–6.0 mg/l), total alkalinity (15.0–21.6 mg/l), nitrate (0.20–0.30 mg/l), phosphate (0.03 – 0.10 mg/l), calcium (2.23–2.50 mg/l) and magnesium (0.56 – 0.70 mg/l).

Table 3: Monthly Means of Chemical Parameters of the Three Water Sources (April – June)

Source	Parameter	April	May	June
Surface water	pH	8.20	8.06	7.90
	EC (µS/cm)	320.0	368.3	359.0
	Total hardness (mg/l)	10.7	9.0	14.3
	Total alkalinity (mg/l)	217.6	224.3	196.6
	Nitrate (mg/l)	1.03	1.03	1.20
	Phosphate (mg/l)	0.53	0.41	0.66
	Calcium (mg/l)	4.30	4.16	4.73
	Magnesium (mg/l)	1.26	0.96	1.24
Groundwater	pH	6.60	6.80	6.00
	EC (µS/cm)	336.6	319.3	359.6
	Total hardness (mg/l)	126.0	122.3	129.3
	Total alkalinity (mg/l)	1202.0	1095.0	1209.3
	Nitrate (mg/l)	3.26	2.93	3.50
	Phosphate (mg/l)	0.32	0.30	0.35
	Calcium (mg/l)	50.40	48.60	51.00
	Magnesium (mg/l)	1.38	1.36	1.44
Rainwater	pH	7.13	7.06	6.70
	EC (µS/cm)	8.0	9.9	10.5
	Total hardness (mg/l)	6.0	5.0	5.3
	Total alkalinity (mg/l)	15.0	21.6	20.0
	Nitrate (mg/l)	0.20	0.23	0.30
	Phosphate (mg/l)	0.05	0.03	0.10
	Calcium (mg/l)	2.40	2.23	2.50
	Magnesium (mg/l)	0.57	0.56	0.70

EC, electrical conductivity. Hardness and alkalinity are expressed as $CaCO_3$. Each value is the mean of three replicates.

Table 4 summarises each parameter as the mean ± SD of the three monthly means for each source, together with the *p*-value of the one-way ANOVA among sources and, where one exists, the drinking-water limit of NIS/SON (2015). The differences among sources are described below.

Physical parameters differed significantly among the sources (Table 4). Surface water had by far the highest colour (1538.3 Pt-Co), turbidity (358.7 NTU) and TSS (177.2 mg/l). Groundwater had the highest TDS (899.4 mg/l), while rainwater had the lowest TDS (67.7 mg/l) and TSS (22.5 mg/l). Mean water temperature was 29.2 °C for surface water, 29.4 °C for groundwater and 23.5 °C for rainwater. Turbidity of the three sources ranged from 13.1 NTU (groundwater) to 358.7 NTU (surface water), and rainwater (63.5 NTU) was more turbid than groundwater.

Among chemical parameters, pH ranged from 6.47 (groundwater) to 8.05 (surface water). Groundwater had the highest total alkalinity (1168.8 mg/l), total hardness (125.9 mg/l), calcium (50.0 mg/l), magnesium (1.39 mg/l) and nitrate (3.23 mg/l), whereas surface water had the highest phosphate (0.53 mg/l). Rainwater had the lowest value of every chemical parameter except pH. Electrical conductivity was similar in surface water (349.1 µS/cm) and groundwater (338.5 µS/cm) and more than 35 times lower in rainwater (9.5 µS/cm). All chemical parameters differed significantly among sources ($p \leq 0.001$). Compared with the limits in Table 4, turbidity exceeded 5 NTU in all three sources, TDS exceeded 500 mg/l in surface water and groundwater, and the mean pH of groundwater (6.47) was slightly below the lower limit of 6.5; EC, total hardness, nitrate and magnesium were within their limits in all sources.

Table 4: Mean ± SD of Physico-Chemical Parameters of the Three Water Sources (*n* = 3 monthly means), ANOVA *p*-Values and The NIS 554:2015 Drinking-Water Limit

Parameter	Surface water	Groundwater	Rainwater	*P*	NIS limit
Colour (Pt-Co)	1538.3 ± 173.6	38.4 ± 5.2	28.7 ± 2.4	<0.001	–
Temperature (°C)	29.2 ± 1.3	29.4 ± 0.4	23.5 ± 0.8	<0.001	–
Turbidity (NTU)	358.7 ± 46.4	13.1 ± 3.2	63.5 ± 47.6	<0.001	5
TSS (mg/l)	177.2 ± 53.8	43.9 ± 5.5	22.5 ± 2.5	0.002	–
TDS (mg/l)	781.7 ± 158.9	899.4 ± 63.4	67.7 ± 4.5	<0.001	500
pH	8.05 ± 0.15	6.47 ± 0.42	6.96 ± 0.23	0.001	6.5–8.5
EC (µS/cm)	349.1 ± 25.6	338.5 ± 20.2	9.5 ± 1.3	<0.001	1000
Total hardness (mg/l)	11.3 ± 2.7	125.9 ± 3.5	5.4 ± 0.5	<0.001	150
Total alkalinity (mg/l)	212.8 ± 14.5	1168.8 ± 64.0	18.9 ± 3.4	<0.001	–
Nitrate (mg/l)	1.09 ± 0.10	3.23 ± 0.29	0.24 ± 0.05	<0.001	50
Phosphate (mg/l)	0.53 ± 0.13	0.32 ± 0.03	0.06 ± 0.04	<0.001	–
Calcium (mg/l)	4.40 ± 0.30	50.00 ± 1.25	2.38 ± 0.14	<0.001	–
Magnesium (mg/l)	1.15 ± 0.17	1.39 ± 0.04	0.61 ± 0.08	<0.001	20

Limits are from NIS/SON (2015); a dash indicates that no limit is specified in that standard.

Figure 3 plots the monthly means of four of the parameters in Tables 2 and 3 that differed most among the sources: turbidity (a), TDS (b), total alkalinity (c) and total hardness (d). In each panel the horizontal axis is the month and each line is one source. In panel (a), surface water had the highest turbidity in all three months and peaked in May, rainwater turbidity declined from April to June until it was almost equal to that of groundwater (10.6 and 10.0 NTU), and groundwater remained low and nearly constant (10.0–16.3 NTU). In panel (b), the TDS of surface water and groundwater lay far above that of rainwater (62.6–70.6 mg/l), groundwater was higher than surface water in every month, and the surface-water value fell sharply in May. In panels (c) and (d), groundwater was clearly separated from the other two sources, with alkalinity above 1000 mg/l and hardness above 120 mg/l in every month, while the lines for surface water and rainwater lay close to the bottom of each panel. The ranking of the sources within each panel was the same in all three months.

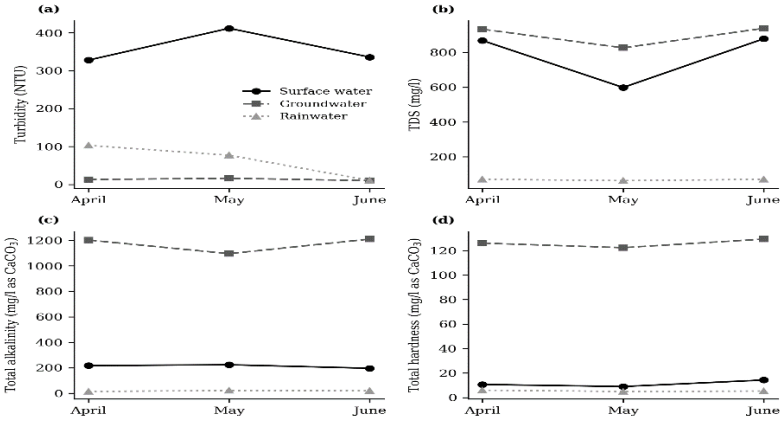

Figure 3: Monthly Variation of (a) Turbidity, (b) Total Dissolved Solids, (c) Total Alkalinity and (d) Total Hardness in The Three Water Sources

Steam Generation

The steam generation results are presented in three steps: the recorded steam temperature and elapsed time at each pressure (Table 5), the same data plotted against pressure (Fig. 4), and the performance indicators derived from them (Table 6).

Table 5 lists, for each source, the steam temperature and the elapsed time at each 0.5-bar step from 1.0 to 7.0 bar (one run per source). Surface water produced steam at 1 bar and 100 °C after 25 min 56 s, and reached the highest pressure of 7 bar (162 °C) after 42 min 20 s. Groundwater produced 1 bar (102 °C) after 25 min 8 s and 7 bar (157 °C) after 40 min 3 s. Rainwater produced 1 bar (65 °C recorded) after 18 min 6 s and 7 bar (156 °C) after 30 min 52 s. At every pressure the elapsed time was shortest for rainwater and longest for surface water.

Table 5: Steam Temperature and Elapsed Time at Each Pressure for The Three Water Sources

Pressure (bar)	Surface water T (°C)	Surface water time (min:s)	Groundwater T (°C)	Groundwater time (min:s)	Rainwater T (°C)	Rainwater time (min:s)
1.0	100	25:56	102	25:08	65	18:06
1.5	103	27:23	106	26:34	98	19:30
2.0	117	29:04	112	27:17	110	21:06
2.5	126	30:35	119	28:35	113	22:04
3.0	133	32:25	127	30:31	123	23:27
3.5	137	33:52	132	31:33	127	24:29
4.0	141	35:22	136	33:13	132	25:32
4.5	145	36:34	140	34:29	137	26:36
5.0	149	37:40	143	35:52	142	27:32
5.5	154	39:22	150	36:47	145	29:09
6.0	157	40:37	152	38:05	149	29:49
6.5	159	41:36	154	39:08	153	30:13
7.0	162	42:20	157	40:03	156	30:52

T: steam temperature; time is elapsed time from the start of heating.

Figure 4 plots the data of Table 5 against pressure: panel (a) shows steam temperature, with the saturation temperature from steam tables as a grey reference line, and panel (b) shows elapsed time. In panel (a), the temperature of every source rose with pressure and, from 1.5 bar upward, lay below the saturation line. From 2.0 bar upward, surface water recorded the highest temperature and rainwater the lowest at each pressure (162, 157 and 156 °C at 7 bar, against a saturation temperature of 165 °C), whereas at 1.0 and 1.5 bar groundwater was higher than surface water, and the first rainwater reading (65 °C at 1 bar) lay far below the saturation line. In panel (b), the rainwater curve lies well below the other two at every pressure and the groundwater curve lies below the surface-water curve, so rainwater reached every pressure level first and surface water last. The gap between the rainwater curve and the other two widens with pressure, from 7 min 50 s (surface water) and 7 min 2 s (groundwater) at 1 bar to 11 min 28 s and 9 min 11 s at 7 bar.

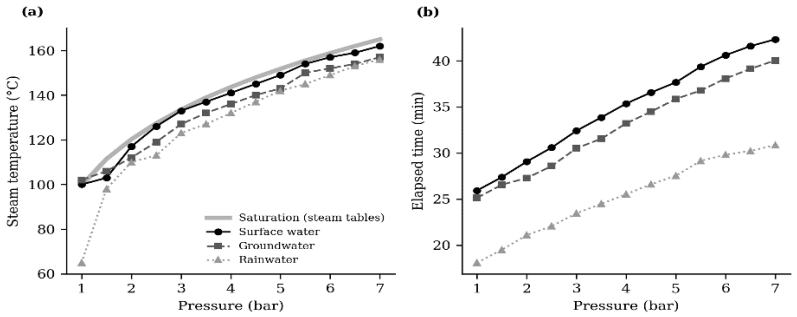

Figure 4: (A) Steam Temperature and (B) Elapsed Time as Functions of Pressure for The Three Water Sources. The Grey Line Is the Saturation Temperature from Steam Tables

Table 6 summarises the indicators derived from Table 5. Rainwater needed 18 min 6 s to reach 1 bar and 30 min 52 s to reach 7 bar, compared with 25 min 8 s and 40 min 3 s for groundwater and 25 min 56 s and 42 min 20 s for surface water. The time taken to rise from 1 to 7 bar was 12 min 46 s for rainwater, 14 min 55 s for groundwater and 16 min 24 s for surface water, giving mean pressure build-up rates of 0.47, 0.40 and 0.37 bar/min, respectively. Relative to rainwater, surface water needed 7 min 50 s (43.3%) longer to reach 1 bar and 11 min 28 s (37.1%) longer to reach 7 bar, while groundwater needed 7 min 2 s (38.9%) and 9 min 11 s (29.8%) longer, respectively. Because the same heater was used for all runs, these heating times translate directly into the relative heater energy to reach 7 bar in the last row of the table: 137 for surface water and 130 for groundwater, taking rainwater as 100.

Table 6: Steam Generation Indicators Derived from Table 5

Indicator	Surface water	Groundwater	Rainwater
Time to 1 bar (mins.)	25:56	25:08	18:06
Time to 7 bar (mins.)	42:20	40:03	30:52
Time from 1 to 7 bar (mins.)	16:24	14:55	12:46
Mean pressure build-up rate, 1–7 bar (bar/min)	0.37	0.40	0.47
Additional time to 7 bar relative to rainwater (mins.)	+11:28	+9:11	–
Additional time to 7 bar relative to rainwater (%)	+37.1	+29.8	–
Relative heater energy to reach 7 bar (rainwater = 100)	137	130	100

Relative energy is the ratio of heating times at constant heater rating.

Discussion

The very high colour, turbidity and TSS of the River Benue water reflect runoff from surrounding surfaces and the suspended and organic matter it carries. Colour is not itself a boiler performance parameter, but together with turbidity it signals organic and colloidal matter that is undesirable in boiler feed water. Turbidity of all sources exceeded the 5 NTU limit for drinking water (NIS/SON, 2015). Suspended solids can be removed by filtration before the water reaches the boiler, but if they enter it they add to the deposits that inadequate feed-water treatment produces (Shokri and Sanavi Fard, 2023). The ranking of the sources was consistent for turbidity and TSS. The relatively high turbidity of rainwater (63.5 NTU), more than that of groundwater, indicates that the harvested rainwater picked up particulate matter during collection; the monthly values (103, 77 and 10.6 NTU) show that this contamination was not constant. This agrees with Nigerian studies in which rainwater harvested from rooftops carried higher physicochemical loads than rain collected directly (Nwachukwu et al., 2023). The surface water was slightly more alkaline (pH 7.9–8.2) than the 5.60–8.00 range reported for the lower River Benue at Makurdi (Otene et al., 2025).

Both TDS (781.7 and 899.4 mg/l) and EC (349.1 and 338.5 µS/cm) of surface water and groundwater were far higher than those of rainwater. TDS of both sources exceeded the 500 mg/l limit of NIS/SON (2015), whereas rainwater was well below it (67.7 mg/l). Electrical conductivity reflects the concentration of dissolved ions, and all sources were below the 1000 µS/cm limit; the surface-water value lies within the range of 210–1890 µS/cm reported for the lower River Benue at Makurdi (Otene et al., 2025). In a boiler, dissolved solids concentrate as steam leaves, which is why TDS, hardness, silica and iron are the parameters that most affect boiler-water treatment in agro-processing mills (Rusdi et al., 2022).

The pH of the three sources (6.47–8.05) lay largely within the 6.5 – 8.5 range of the drinking-water standard, with the exception of groundwater, whose mean (6.47) and June value (6.0) fell slightly below the lower limit. The pH of raw feed water is of secondary importance for the boiler, because BS 2486 recommends that boiler water be maintained at pH 10.5–12.0, outside which the corrosion rate of steel rises significantly (BSI, 1997). All three sources would therefore need chemical conditioning to reach that range.

Total alkalinity was the most discriminating parameter: 1168.8 mg/l in groundwater, 212.8 mg/l in surface water and 18.9 mg/l in rainwater. High alkalinity in feed water favours the formation of chemical deposits, and a deposit layer on a heated surface raises the resistance to heat transfer, so more energy is needed for the same steam output (Al-Gailani et al., 2021). Inadequately treated feed water can also lead to corrosion and boiler failures (Shokri and Sanavi Fard, 2023). The groundwater alkalinity is much larger than its hardness (125.9 mg/l), which indicates that most of the alkalinity is not associated with calcium and magnesium and therefore calls for dealkalisation or blowdown management rather than softening alone.

Total hardness and calcium were highest in groundwater (125.9 and 50.0 mg/l) and below the 150 mg/l hardness limit for drinking water. Hardness, however, is more critical for boilers than for drinking water: in a 30-day field study of an industrial fire-tube boiler, feed-water hardness showed a strong negative association with thermal efficiency ($R^2 \approx 0.96$) (Bashori and Subrianto, 2026), and calcium carbonate scale is the main deposit that forms on heated surfaces from hard water (Al-Gailani et al., 2021). Magnesium (0.61–1.39 mg/l) was far below the 20 mg/l limit, and nitrate (0.24–3.23 mg/l) was far below the 50 mg/l limit; neither is a primary concern. Phosphate was low in all sources (0.06–0.53 mg/l).

The central result of this work is that the cleaner the feed water, the sooner steam was raised. Rainwater, with the lowest TDS, alkalinity and hardness, reached 7 bar in 30 min 52 s, while groundwater and surface water needed 29.8% and 37.1% more time (Table 6). Because the heater rating was the same for all runs, this corresponds directly to about 30% and 37% more electrical energy per start-up to reach 7 bar. This agrees with the established view that impurities in feed water lead to deposits, reduced heat transfer and higher energy consumption (Bashori and Subrianto, 2026; Al-Gailani et al., 2021). The ranking of the sources also matches their solids load: surface water, which carried the highest suspended solids, colour and turbidity as well as high TDS and alkalinity, was the slowest, and groundwater, with the highest TDS, alkalinity and hardness, was second. It is notable that rainwater, which was slightly cooler (23.5 °C) than the other sources, still reached steam conditions first.

From 2.0 bar upward, the recorded steam temperature was highest for surface water and lowest for rainwater (Fig. 4a); at 7 bar the readings were 162, 157 and 156 °C, against a saturation temperature of 165 °C. The magnitude of these differences is, however, much greater than the boiling-point elevation expected from the dissolved solids present, which is of the order of hundredths of a degree at these TDS levels. They are therefore more likely to reflect differences in heat transfer and temperature-sensor response in the boiler than a direct effect of the dissolved solids, and the temperature results should be interpreted with caution. The first rainwater temperature reading (65 °C at 1 bar) is well below the saturation temperature and is reported as recorded.

For a rice processing plant, the results suggest that the three sources should not be treated as interchangeable. Harvested rainwater gave the fastest and most energy-efficient steam generation and had the lowest scaling potential, but its availability is seasonal and it must be collected and stored cleanly, because catchment surfaces can add particulate and chemical load (Nwachukwu et al., 2023). Surface water needs

clarification and filtration to remove colour, turbidity and suspended solids. Groundwater needs treatment for alkalinity, TDS and hardness, for example by softening supplemented by chemical conditioning and blowdown control based on the cycles of concentration (Shokri and Sanavi Fard, 2023; Rusdi et al., 2022). In all cases, boiler feed water should be tested against the standard required for the boiler type and operating pressure.

CONCLUSION

Surface water, groundwater and rainwater in Makurdi differ markedly in quality, and these differences translate into differences in the time and energy needed to generate steam. Surface water had the highest colour, turbidity and suspended solids, groundwater had the highest dissolved solids, alkalinity, hardness and calcium, and rainwater was the cleanest on most parameters. Rainwater reached 7 bar in 30 min 52 s, whereas groundwater and surface water needed 29.8% and 37.1% longer, equivalent to about 30% and 37% more heater energy at a constant rating. The high alkalinity of the groundwater (1168.8 mg/l) and the solids load of the surface water are the main concerns for deposit formation, reduced heat transfer and corrosion in a plant boiler.

It is recommended that; the quality of every source be assessed against the standard required for the boiler type and operating pressure before the source is adopted; surface water be clarified and filtered, and groundwater be softened and dealkalised, supplemented by chemical conditioning of the boiler feed water to limit deposits and corrosion; and metered, replicated tests be carried out on a plant-scale boiler to confirm the energy penalty.

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