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Assessment of the Cagayan Valley Aquifer System: Groundwater Development in Metropolitan Tuguegarao

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Abstract *– Metropolitan Tuguegarao Water District is one of Northern Luzon's leading groundwater consumers, averaging a monthly extraction of 1.43 million cubic meters. Since its inception, the water supply system has relied mainly on groundwater, triggering well sources to deteriorate. While recharge through soil moisture accounting is sufficient for safe yield estimation, a groundwater flow model was created to account for the spatiotemporal distribution of groundwater levels in response to hydraulic and hydrologic stresses. MODFLOW, a finite-difference model, aided in the development of local grids from a regional basin—the Cagayan Valley Aquifer System. A three-dimensional numerical flow model was satisfactorily calibrated, with the goodness of fit between the simulated and observed heads determined through three statistical indices: Mean Absolute Error (0.5376 m), Root-Mean-Squared Error (0.8061 m), and Normalized Root-Mean-Squared Error (2.23%). The model simulated a 10.60% recharge from rainfall for the regional basin, which is comparable to the average recharge rate estimated by the Department of Environment and Natural Resources. Continuous pumping demonstrated head reductions that exceeded critical levels in four wells at current rates, 12 wells at adjusted rates, and five wells affected by pumping the proposed wells. Notably, four production wells, which constitute 31% of the present groundwater production, remained below critical levels. With the proposed surface water facility, however, groundwater production may be reduced up to 63%, allowing for the resource to recover. The findings of this research on all model scenarios showed that groundwater levels will decrease in the coming years. Thus, efficient planning for sustainable resource use is crucial. This study presents the relevance of numerical hydraulic analysis for a more comprehensive groundwater resource assessment.*

Keywords*: drawdown, groundwater sustainability, hydraulics, local grid, MODFLOW*

I. INTRODUCTION

Worldwide field conditions revealed that groundwater is extracted more rapidly than replenished, with the global abstraction rate reported to have tripled over the last 50 years to compensate for the increasing demand for fresh water [1]. In the Philippines, a report estimated an average annual increase of 5.3% in groundwater demand, with the natural recharge from rainfall decreasing annually at 3.7%. Such a balance implied a significant 1.4% yearly drop in the country's closing stock of groundwater [2], raising concerns on the sustainable use of the resource.

In Northern Luzon, Cagayan Valley is one of the regions presently experiencing water scarcity [3]. With the Cagayan River Basin (CRB) assessed to likely encounter water availability deficits by 2025, appeals for water resource development programs to combat climate change and watershed degradation are necessary [4]. The water rights permitted by the National Water Resources Board (NWRB) revealed that 94% of domestic and municipal water demands in the region were sourced from groundwater. Remarkably, the Metropolitan Tuguegarao Water District (MTWD) is the largest resource consumer not only in the region but in the entire Northern Luzon, with an average monthly groundwater production of 1.43 million cubic meters [5]. With this massive output relying solely on groundwater, well sources have deteriorated in terms of yield and quality [6]. Consequently, groundwater overextraction led to questions on resource sustainability, exacerbated by the escalating number of consumers, expanding service areas, lack of facilities and new water sources, and high levels of non-revenue water. Currently, there are 41,186 active service connections. Considering population projections recommended by the MTWD, the production rates from the existing wells can no longer provide the demands by 2033 and a 35% increase in production is crucial to sustain water demands until 2050.

The majority of studies encompassing CRB, where the metropolitan is located, employ water balance models for sustainability assessment. However, the results are conventionally lumped on a basin scale, omitting repercussions of the variability in groundwater utilization, especially in wellfields with considerable extraction. Although water balance modeling is generally practical, the approach does not account for groundwater flow and availability as site-specific and time-variant, which limits the spatiotemporal analysis of the finite source [7,8]. To fill this gap, this study implements a science-based alternative through numerical simulations of groundwater flow that can provide a more accurate and detailed estimate of groundwater levels, showing more relevance in characterizing groundwater conditions to the evolving needs and challenges in the metropolitan's water supply. With this research assessing hydrologic scenarios and pumping implications on groundwater, the simulation results may serve as bases for concerned units and agencies in planning, formulating, and implementing sustainable groundwater management policies.

Groundwater flow models have proven efficiency in various engineering applications and one of the most extensively used programs is the MODFLOW, an open-source modular three-dimensional finite-difference groundwater flow model developed and distributed by the USGS [9]. For more than 30 years, the program has served various industries—academe, government, private agencies, researchers, and scientists—making it an international standard in flow simulation and prediction.

Despite this advancement, however, modeling water resources systems in the Philippines is generally not very common [10], as investments in science-based management and decision-making tools are unprioritized, aggravated by inadequate data required for model calibration and validation. Notwithstanding these factors, few local researchers still made efforts to pursue groundwater modeling applications.

For instance, Quitaneg [11] investigated the groundwater potential in Concepcion, Tarlac using MODFLOW, wherein changing conditions in industrial, domestic, and agricultural water use yielded a 38.5% increase in discharge rate per well by 2030. Ella [12] also utilized MODFLOW to simulate and quantify the impacts of climate change on groundwater levels in a shallow aquifer Maitim, Bay, Laguna. In the absence of quality hydrogeologic data, a generic model was created.

Globally, flow models have shown dominance in assessing resource sustainability in response to various pumping regimes. In India, the largest groundwater user in the world, Kirubakaran et al. [13] created a groundwater flow model to quantify groundwater availability in Tirunelveli Taluk, Tamil Nadu, wherein a negative water budget in 2011 was simulated. Also in India, Sahoo and Jha [14] simulated groundwater flow in the Mahanadi River delta using MODFLOW. The response of the aquifers to variations in recharge and pumping conditions was compared, revealing that pumping is more considerable in the confined aquifer flow regime than in the unconfined aquifer. For coastal areas, saltwater intrusion is probable. Thus, Itoua-Tsele et al. [15] applied MODFLOW to assess the coastal aquifers of Pointe-Noire, Congo by mainly focusing on the effects of intensive groundwater exploitation of 14 high-performance wells over a 10, 15, 20 and 25-year simulation. Large drawdowns and extensive seawater intrusion were simulated given abstraction from all wells. Gomez Arevalo [16] also developed a regional groundwater flow model to determine if the current groundwater pumping regime in Carraipia Basin, La Guajira, Colombia is environmentally sustainable.

The seasonality or fluctuations in groundwater demand and production were incorporated into these research strategies. Thus, numerical flow models address gaps imposed by traditional methods like water balancing or soil moisture accounting. Lumped recharge values restrict analysis of a concise groundwater dynamics, which is theoretically altered by the geologic distribution of strata and seasonal water demands [7,8]. Therefore, flow models are more representative of the physical conditions, where groundwater is an intrinsic function of space and time.

This research aims to assess groundwater sustainability in Metropolitan Tuguegarao using the MODFLOW program. Specifically, it involves the development of conceptual and numerical models, where groundwater conditions will be assessed based on model simulations, to describe trends in groundwater levels properly and make recommendations for sustainability.

II. METHODOLOGY

This study made use of the MODFLOW program for groundwater sustainability assessment in Metropolitan Tuguegarao. The workflow of the modeling process is shown in Figure 1, which was modified from the studies of Mondal [17] and Fouad et al. [18]. The research methodology was composed of three main stages—the model setup comprising both conceptual and numerical modeling; model calibration, consisting of the validation and sensitivity analysis; and model implementation, referring to the scenario analyses. The simulation results were used to evaluate drawdowns in each wellfield and infer well sustainability based on the critical pumping levels imposed by the MTWD.

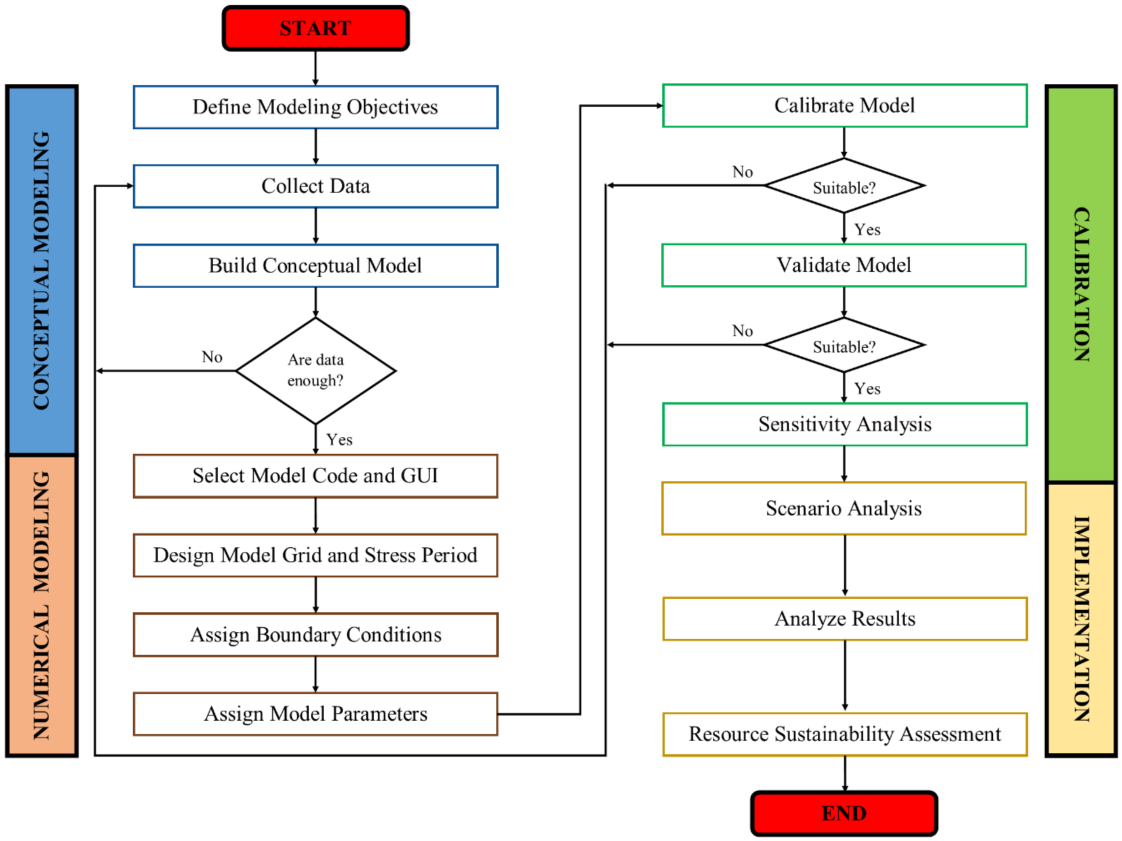


Figure 1. Methodological Framework

2.1. Data Acquisition and Preparation

Well-construction and production data were provided by the MTWD, supplemented by the Philippine Groundwater Databank [19] of the Local Water Utilities Administration (LWUA). Hydrogeologic data were requested at the Mines and Geosciences Bureau (MGB) Region 2. Meteorological data were obtained from the PAGASA (i.e., from 2011 to 2022) and NASA POWER Project (i.e., from 1981 to 2010) to quantify hydrologic stresses. Due to data inadequacy, mean values were used from 1955 to 1980. The datasets collected were imported, georeferenced, digitized, and postprocessed into raster and vector files in QGIS, an open-source geographic information software, as required in the modeling process.

2.2. Numerical Modeling

2.2.1. The Conceptual Model and Boundary Conditions

Before a numerical model was developed, the study area and its hydrogeologic processes was conceptualized [20]. The conceptual model is simply a description of the aquifer system [12]. Although a generic geological framework is allowed [20], a site-specific hydrogeological setting was developed in this study. A regional flow system, termed the Cagayan Valley Aquifer System in this research, was conceptualized to determine appropriately the boundary conditions of the local basin [9], Metropolitan Tuguegarao. The boundary conditions simulate hydrologic stresses spatiotemporally and are generally classified into three categories: Specified Head or Dirichlet, Specified Flux or Neumann, and Head-Dependent Flux or Cauchy.

Specified-head boundaries simulate features with known hydraulic heads. Being the most critical conditions [20], however, constant heads were avoided in this research. Specified-flux boundaries simulate features with known flow rates, which include recharge, well discharge, and no-flow conditions. Finally, head-dependent fluxes entail the requirement for two heads to calculate flow. Evapotranspiration and river were conceptualized as head-dependent fluxes.

The Cagayan Valley Aquifer System was based on CRB's physical features. The groundwater divides were assumed to coincide with the watershed ridges, since the geologic outcrops of the foundations lie on similar locations. Moreover, faults were defined as flow barriers [9]. The mountainous areas, characterized by soils with high infiltration capacity [21], receive more rainfall. Thus, a correlation between elevation and rainfall was theorized in the model for recharge estimation, assuming the highlands as recharge areas. The conceptualized model for the aquifer system is shown in Figure 2.

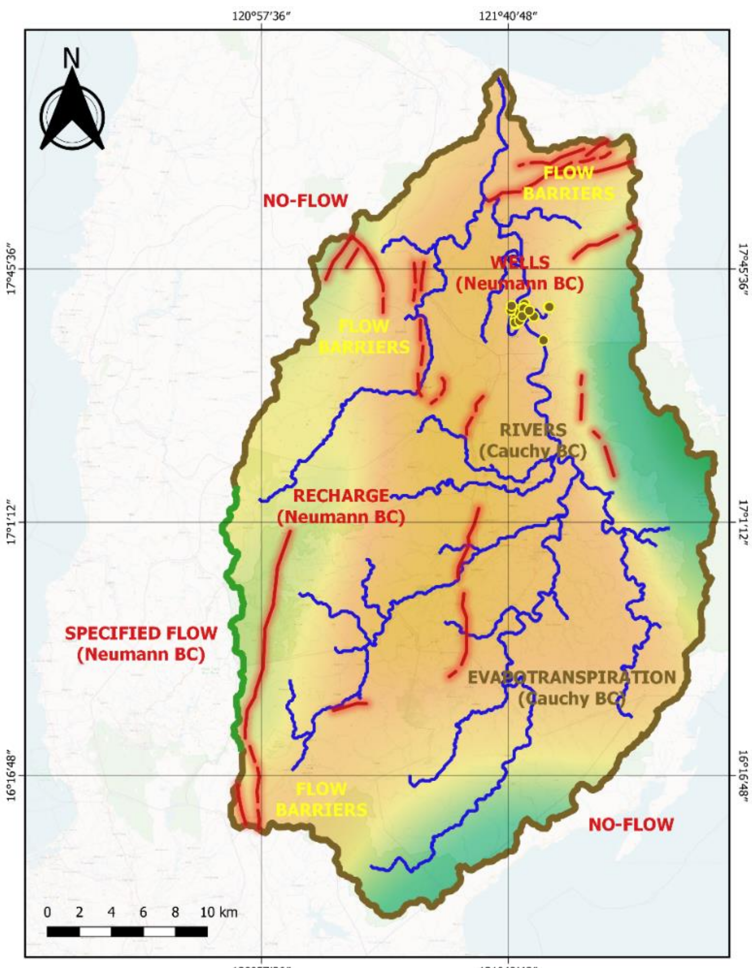


Figure 2. Conceptualized boundary conditions of the aquifer system

2.2.2. Spatial Discretization

The numerical model was discretized, as presented in Figure 3. The regional model was assigned four layers, where each cell measures 1 km by 1 km. With MODFLOW's local grid refinement (LGR) capability, finer cells were assigned to the local area or child model for greater simulation accuracy. By default, the number of rows and columns is the same for all model layers. A 5:1 refinement ratio was set horizontally for the child model, creating 200 m by 200 m finer cells. There were no available data concerning the thicknesses of the units hence conceptualized, as shown in Table 1. The aquifer system's last layer was assumed to lie 500 m below mean sea level, in consistent with the JICA's study for CRB.

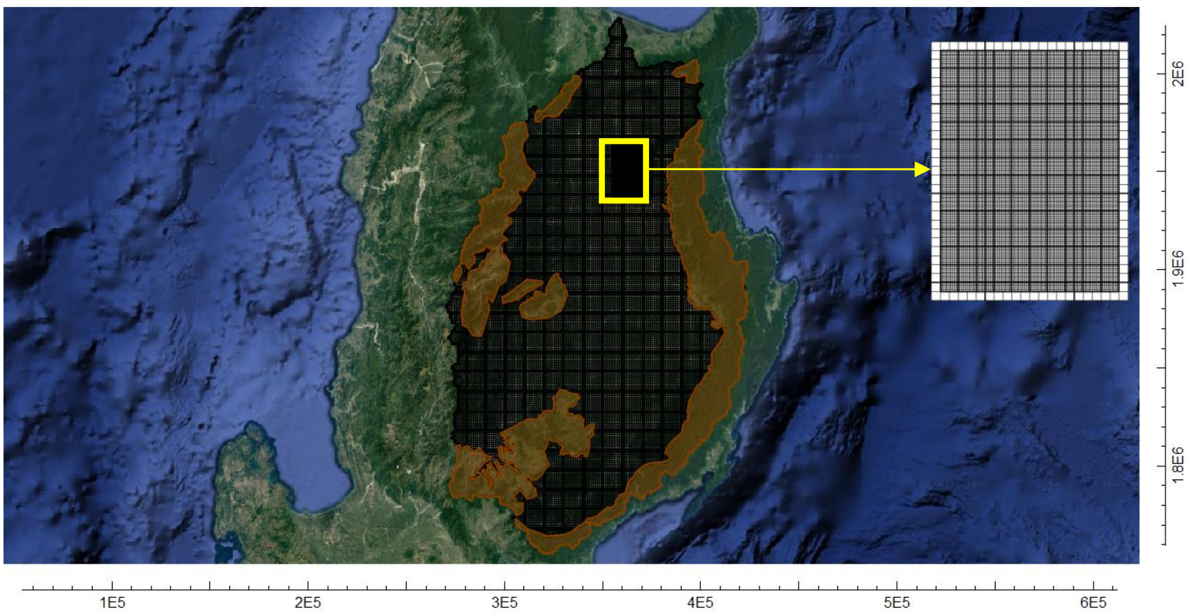


Figure 3. The model grid design

Table 1. Vertical distribution of layer groups

Model Layer	Bottom Location
Recent Alluvium	Interpolated
Pliocene-Pleistocene	Recent Alluvium – 100 m
Oligocene-Miocene	Pliocene-Pleistocene – 100 m
Cretaceous-Paleogene	500 m below mean sea level

2.2.3. Parameterization

Although well logs were available, site-specific parameters like hydraulic conductivity were not readily characterized by the MTWD. Only the borehole data from JICA included permeability test results. Alternatively, property values for materials excluded in the JICA data were inferred based on representative ranges from the literature. With insufficient data pertaining to the hydraulic conductivity values of the subsequent layers, it was assumed that all rocks of similar class had comparable hydraulic properties and were assigned related hydraulic conductivity values [22]. Similarly, the majority of hydraulic properties were approximated on the most dominant or contributing hydrogeologic unit per layer.

2.3. Statistical Analysis for Calibration and Validation

Since this research employed numerical modeling, the reliability of the model in reproducing observed data under field-measured hydrologic conditions was measured. Model parameters were adjusted, and sets of simulated and observed data were compared until an acceptable match between values was obtained [23]. Hydraulic head records between 1955 and 2017 from 41 observation wells served as calibration targets. Furthermore, water levels of 145 wells observed by the MGB in 2018 were used for verification. This study applied summary statistics such as Mean Absolute Error (MAE), Root-Mean-Square Error (RMSE), and Normalized Root-Mean-Square Error (RMSE) to measure the goodness-of-fit between simulated and observed heads. The guidelines are presented in Table 2. By default, R^2 is MODFLOW-computed to infer the percent of observed heads that can be explained by the model.

Table 2. Guidelines in evaluating performance of flow models

Statistical Metric	Criterion
MAE & RMSE	Values less than half the standard deviation of the measured data may be considered low and appropriate for model evaluation [24]
NRMSE	Values less than 10% imply an acceptable groundwater model [25]

2.4. Model Scenarios

The existing discharges of 18 production wells were maintained in this study to assess changes in water levels when current pumping is sustained. Then, based on the population data, demand was projected and the existing rates were adjusted equally for all wells. The MTWD's business plan also incorporated three proposed wells (i.e., CAG-TUG-147, CAG-TUG-148, and CAG-TUG-149) and a surface water facility [26]. To optimally infer resource sustainability, all simulations were aimed to approximate new steady conditions (i.e., approximately zero change in storage) to obtain the maximum head reduction of all wells. The summary of model scenarios is presented in Table 3.

Table 3. Pumping strategies considered for simulation

Scenario	Pumping Setup
MTWD-1	Steady pumping levels were achieved by maintaining the present rates imposed by the MTWD for 18 wells.
MTWD-2	Steady pumping levels were achieved by increasing the present rates based on the projected water consumption of the area.
MTWD-3	Steady pumping levels were achieved by maintaining the present rates with the addition of three proposed wells: CAG-TUG-147, CAG-TUG-148, and CAG-TUG-149.
MTWD-4	Steady pumping levels were achieved by reducing the present rates to account for the 30 MLD contribution from surface water.
MTWD-5	Steady pumping levels were achieved by increasing the present rates based on the projected water consumption of the area, and accounting for the 30 MLD contribution from surface water.
MTWD-6	Steady pumping levels were achieved by reducing the present rates with the addition of three proposed wells: CAG-TUG-147, CAG-TUG-148, and CAG-TUG-149, and accounting for the 30 MLD contribution from surface water.

III. RESULTS AND DISCUSSION

3.1. Hydrogeologic Features of the Cagayan Valley Aquifer System

3.1.1. Geological Formations

Figure 4 reveals the local area is entirely of sedimentary form, made of recent alluvium from the Quaternary series. The city's eastern portion has older formations dating back to the Pliocene to Pleistocene epoch. Generally, the regional groundwater basin has deposits from five geologic epochs: (1) Cretaceous and Paleogene (i.e., 66 million years ago) characterized largely by graywacke and metamorphosed shale; (2) Oligocene to Miocene (i.e., 33.9 million years ago) described by marine deposits, wackes, shales, and reef limestone; (3) Upper Miocene to Pliocene (i.e., 23.03 million years ago) made of marine clastics and tuffaceous sedimentary rocks; (4) Pliocene to Pleistocene (i.e., 5.33 million years ago) characterized by marine and terrestrial molasses with extensive reef limestone; and the (5) recent alluvium from the Quaternary series (i.e., 2.58 million years ago).

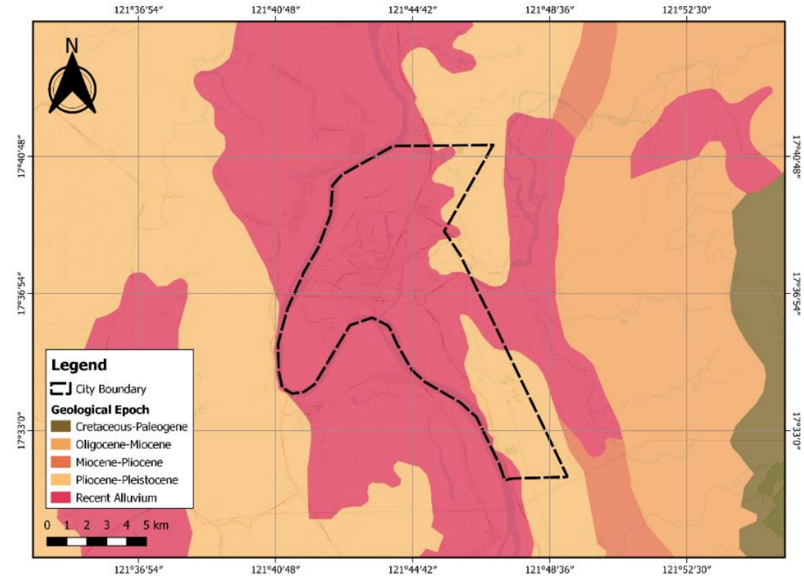


Figure 4. Geologic map of Metropolitan Tuguegarao

3.1.2. Hydrogeologic Units and Characteristics

Figure 5 presents three major hydrogeologic units defined by the MGB in the area. These encompass rocks in which flows are dominantly intergranular, dominantly through fractures, and generally without significant groundwater obtainable.

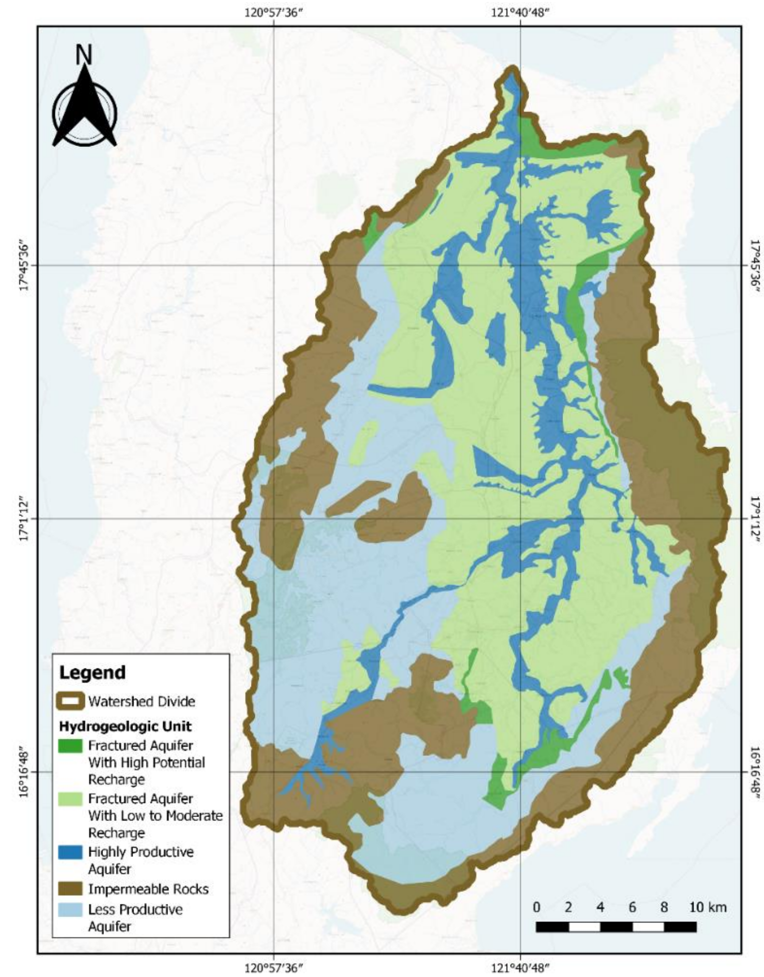


Figure 5. Hydrogeologic units within the Cagayan Valley Aquifer System

Intergranular rocks are divided further into highly and less productive aquifers. Highly productive intergranular aquifers have high to very high permeability—mostly between 50 to 100 l/s but as high as 150 l/s in some sites. These sites are often characterized by Quaternary thick unconsolidated sand and gravel aquifers in the flood plains. On the other hand, less productive aquifers yield mostly about 2 to 20 l/s. These include Pliocene to Pleistocene semi-consolidated to unconsolidated sediments, and Upper Miocene to Pliocene sediments and volcanics, mainly sandstone, shale, and conglomerate.

Fractured rocks are also divided as fairly extensive and productive aquifers with high potential recharge and fairly to less extensive and productive aquifers with low to moderate potential recharge. High potential recharge areas yield mostly 5 to 15 l/s, which encompass Pliocene to Pleistocene and Lower to Upper Miocene coralline limestones. Rocks with few interconnected solution cavities, known to yield 3 l/s or less, comprise fractured aquifers with low to moderate potential recharge.

Rocks without any known significant water obtainable through drilled wells are composed of undifferentiated Cretaceous to Paleogene strata, commonly mapped as metavolcanics and metasediments. Combining all hydrogeologic and geologic formation conceptualizes the schematic cross-section of the Cagayan Valley basin, as illustrated in Figure 6.

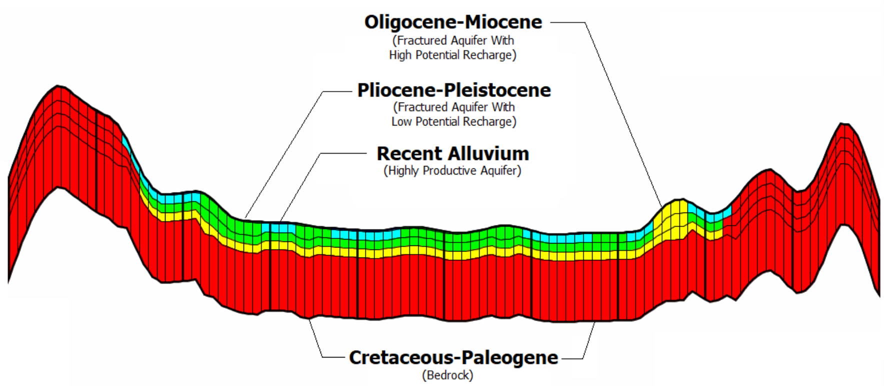


Figure 6. Schematic cross-section of the Cagayan Valley Aquifer System

3.1.3. Stratigraphic Profile within Metropolitan Tuguegarao

MWTD well logs were used to define the layers within Metropolitan Tuguegarao. The borehole depths range between 12 m and 110 m. Low-permeable materials, primarily clay and silt with thickness varying from 0.60 to 71 m, compose the upper layer. The underlying layer is an aquifer predominantly composed of gravel and sand as part of the Quaternary alluvial deposits. This layer information is consistent with Figure 6, verifying the conceptualized layers for the aquifer system.

3.1.4. Hydrometeorology

The southwest monsoon brings heavy rainfall in the metropolitan from June to November. Monthly rainfall values during this period range between 32 mm and 550 mm. PAGASA estimated the normal annual rainfall in the area to be 1768.90 mm. Rainfall is the only recharge source of local aquifer systems in the study area, wherein an estimated 10.65% of annual rainfall recharges aquifers in the basin [27]. Basin annual rainfall varies from less than 2,000 mm in the lowland to more than 4,000 mm in the mountainous areas.

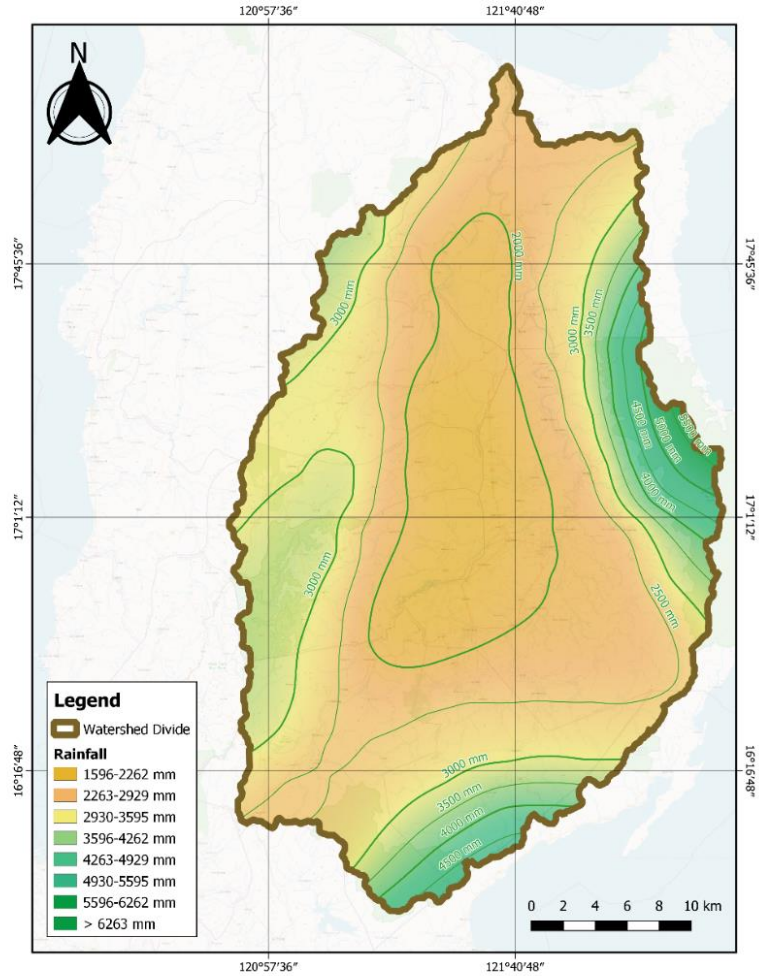


Figure 7. Average annual rainfall

On the other hand, a hot and dry climate is prevalent from February to May. The basin-scale spatial distribution of average monthly evapotranspiration is illustrated in Figure 8.

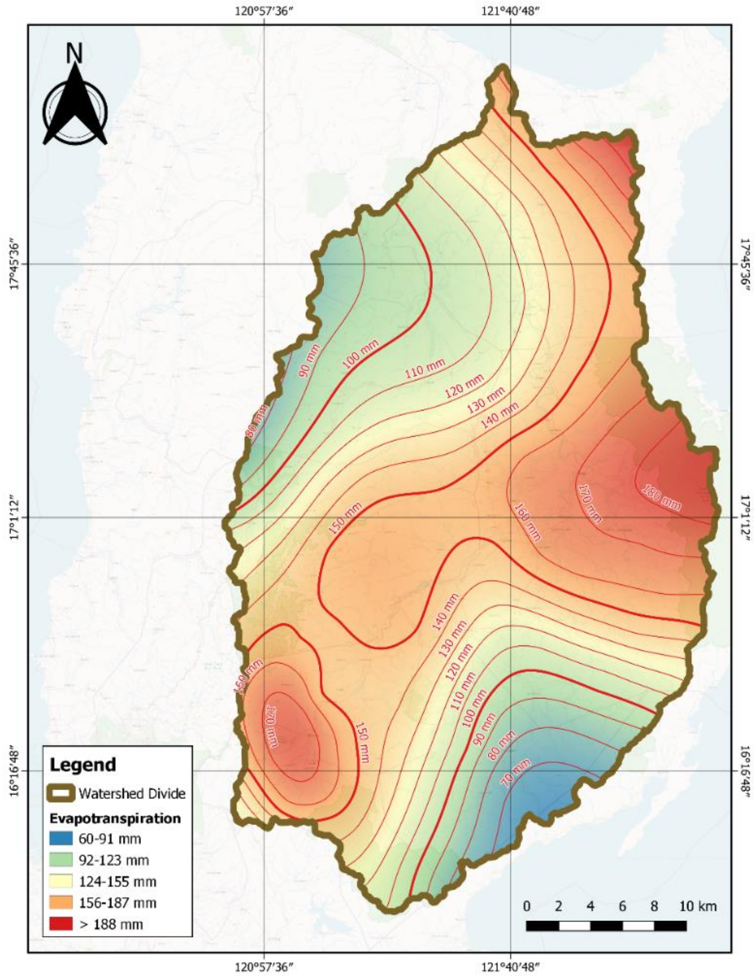


Figure 8. Mean monthly evapotranspiration

3.1.5. Pumping Rates and Water Levels

There are currently 18 high-capacity active wells operated by the MTWD for the Tuguegarao system, as presented in Figure 9, with Table 4 showing the well yield ranges from 9 to 52 liters per second (l/s). Most of the wells are clustered or located close to each other.

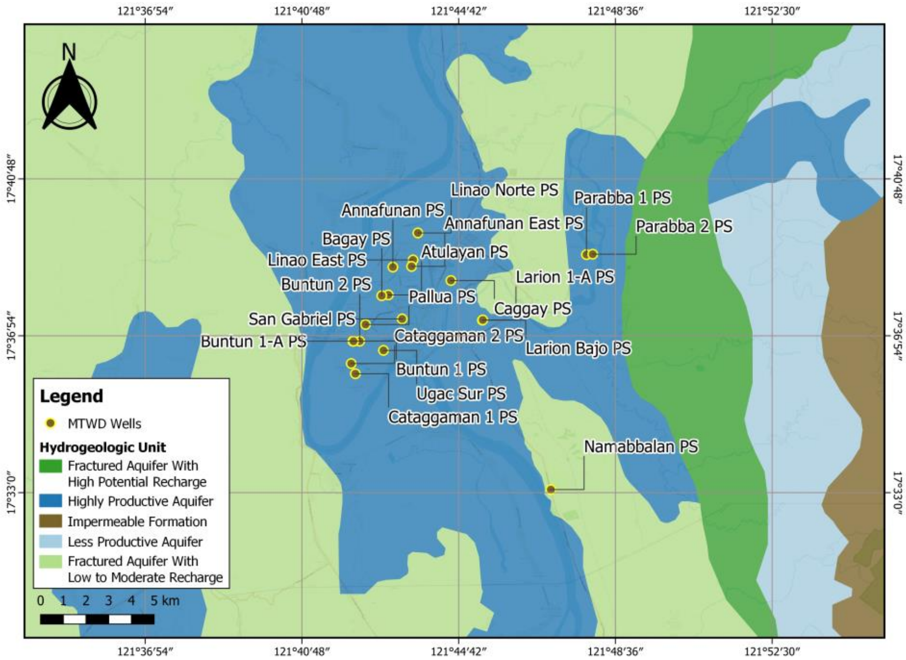


Figure 9. Location of MTWD wells

Table 4. Well inventory within Tuguegarao system

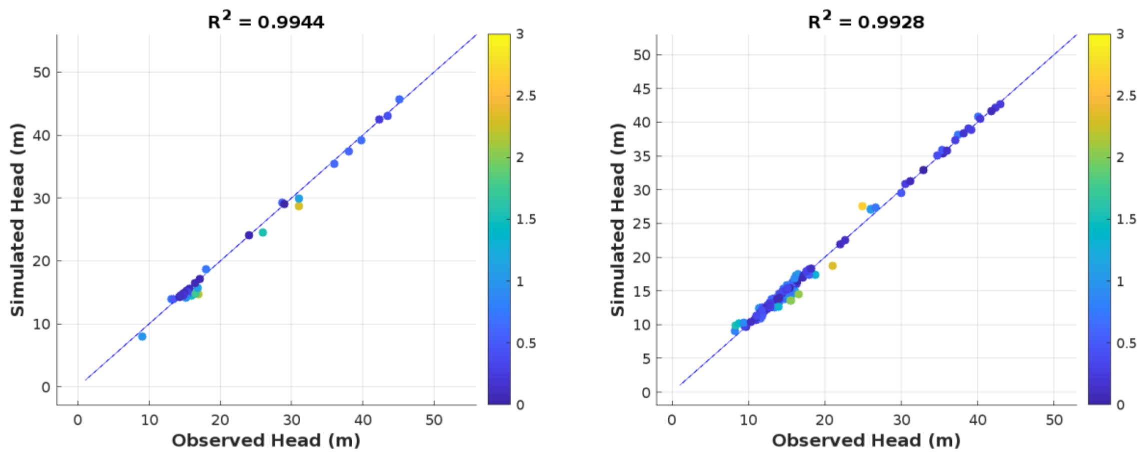
LWUA ID	Station	Yield (l/s)	LWUA ID	Station	Yield (l/s)
CAG-TUG-1	Buntun 1	28	CAG-TUG-11	Namabbalan	9
CAG-TUG-2	Buntun 2	22	CAG-TUG-12	Cataggaman 2	52
CAG-TUG-3	Pallua	30	CAG-TUG-13	Larion 1-A	46
CAG-TUG-5	Annafunan	49	CAG-TUG-14	Atulayan	44
CAG-TUG-6	Linao Norte	30	CAG-TUG-15	Bagay	45
CAG-TUG-7	Larion Bajo	31	CAG-TUG-16	Ugac Sur	23
CAG-TUG-8	Buntun 1-A	34	CAG-TUG-17	Annafunan East	30
CAG-TUG-9	Cataggaman 1	13	CAG-PEN-23	Parabba 1	41
CAG-TUG-10	Linao East	26	CAG-PEN-24	Parabba 2	52

3.2. Calibration and Validation

Most wells used for calibration are located in Cagayan and Isabela. Table 5 shows the statistical values during model calibration. Half of the standard deviation of observed heads is 4.9203 m, setting the upper limit for MAE and RMSE; both are lower than this value. NRMSE is equal to 2.23%, lower than the maximum limit of 10%. NSE is at 0.5537, implying a satisfactory performance level. This indicates that the model is adequate for all statistical metrics within the context of groundwater flow, with the best fit line between simulated and observed heads yielding coefficient of determination R^2 of 99.4% during calibration, as shown in Figure 10.

Table 5. Statistical indices for the calibrated model

Metric	Computed Value	Criterion
MAE	0.5376 m	< 4.9203 m
RMSE	0.8061 m	
NRMSE	2.23%	< 10%
NSE	0.5537	0 to 1, > 0.50 (satisfactory)



(a) *(b)*

Figure 10. Best line of fit during (a) calibration and (b) validation

Table 6. Statistical indices during validation

Metric	Computed Value	Criterion
MAE	0.5087 m	< 4.0948 m
RMSE	0.6982 m	
NRMSE	2.01%	< 10%
NSE	0.4924	0 to 1, > 0.50 (satisfactory)

A separate simulation was run to verify the calibrated model using observed water levels in 2018. Table 6 suggests every statistical metric still satisfied their corresponding criteria at 99.28% accuracy. Figure 11 presents the sensitivity of model results to changes in the parameters. The study adopted the sensitivity threshold by Sahoo and Jha [14]: high sensitivity if the coefficient exceeds 0.09, moderate sensitivity from 0.05 to 0.09 and low sensitivity for values less than 0.05. These values signify that for every percent change in the input, the head targets will change by an amount equal to the sensitivity coefficients. Highly sensitive parameters were prioritized during calibration, while low to moderate parameters were retained to maintain acceptable values. Recharge (RCH), the sole inflow to the aquifer system, is intrinsically a highly sensitive parameter. The horizontal hydraulic conductivity of sand and gravel (K2) was found to be the most sensitive parameter, followed by the hydraulic conductivity of Oligocene-Miocene formations (K4). Reducing the vertical hydraulic conductivity (Kz) of layers increased the hydraulic heads as flow between layers was constrained. Specific yield (SY) and specific storage (SS) showed low impact to model results. Increasing conceptualized layer thicknesses (LTHK) also yielded an upsurge in water levels.

Inversely, reducing layer thickness decreased the heads. The assumed thicknesses were then retained as these were where the model parameters were established.

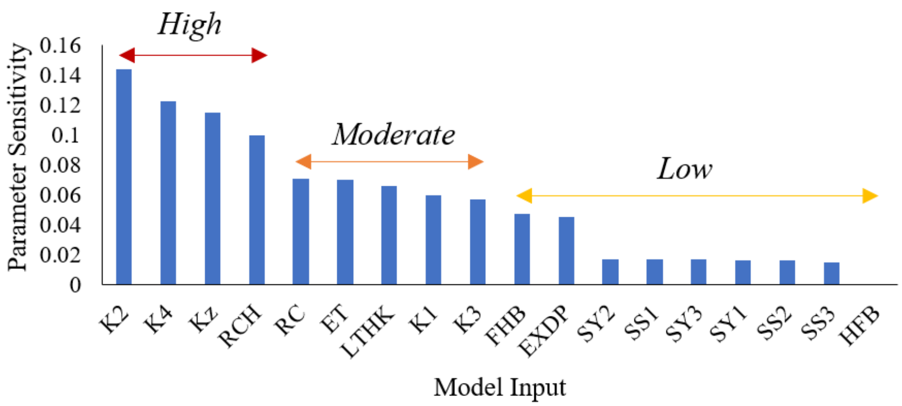


Figure 11. Sensitivity of groundwater hydraulic parameters

The model was considered optimal after the parameter adjustments as the model fit cannot be further improved for all metrics [20,23]. A minimal discrepancy was consistently maintained such that changes to the enhanced parameters are sufficiently small that one is not substantively different from another. Zero discrepancies for the child grid, Metropolitan Tuguegarao, were achieved for all iterations in every stress period, which suggests that further calibration is not necessary for the main study area.

3.3 Groundwater Dynamics

Figure 12 illustrates the approximated steady-state groundwater flow of the aquifer system. The simulated heads are heavily influenced by the area's topography—a hydrogeologic principle often used for the preliminary characterization of flow systems since water tables are generally conceptualized as subdued replicas of topography. The main input to the regional model is through recharge from rainfall in the highlands. Accordingly, the model simulated high water levels in the recharge areas: Cordillera, Caraballo, and Sierra Madre Mountain ranges, where mountain soils with high infiltration capacity are characterized [21]. Limestones, sandstones, shales, conglomerates, and similar rock formations underlie these elevated portions, producing steep gradients defined by closely spaced potentiometric contours [28]. A more expansive space between contours is evident in plains (i.e., middle portion of the basin), inferring smaller gradients. Underlying formations in these areas are sedimentary, mostly of recent alluvium. Since groundwater naturally flows from high elevation to low elevation and from high pressure to low pressure, upstream water is potentially discharged into the Cagayan River and its tributaries, situated in the relatively low elevations of the basin. Water table gradient even increases near the discharge locations due to convergence of flow. Low water levels are found downstream, with the lowest head simulated near the basin outlet in Aparri at 0 masl.

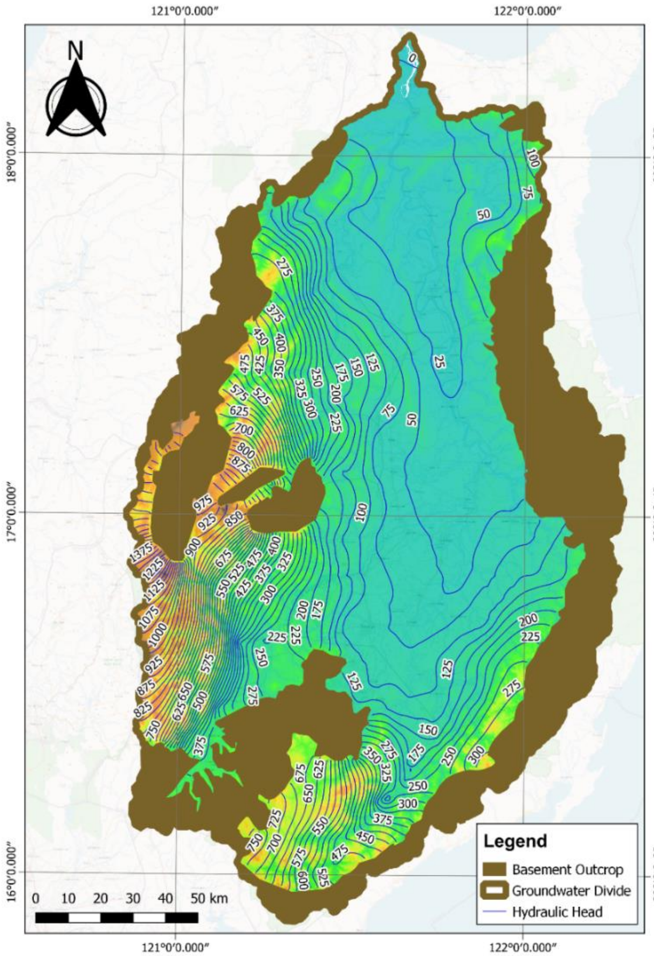


Figure 12. Steady groundwater-flow conditions of the Cagayan Valley Aquifer System

Figure 13 presents water flows from the southwest and east portions of the metropolitan and converges in the flat terrains. Dense equipotential lines, indicating faster groundwater velocity, are discernible in the elevated regions. In contrast, sparse equipotential lines are found in the central portion, characterizing more stable or sluggish groundwater movement. Aside from the metro's nearly flat topography, low hydraulic gradients are common in sandy and gravelly geology [29], such as the area's investigated geology.

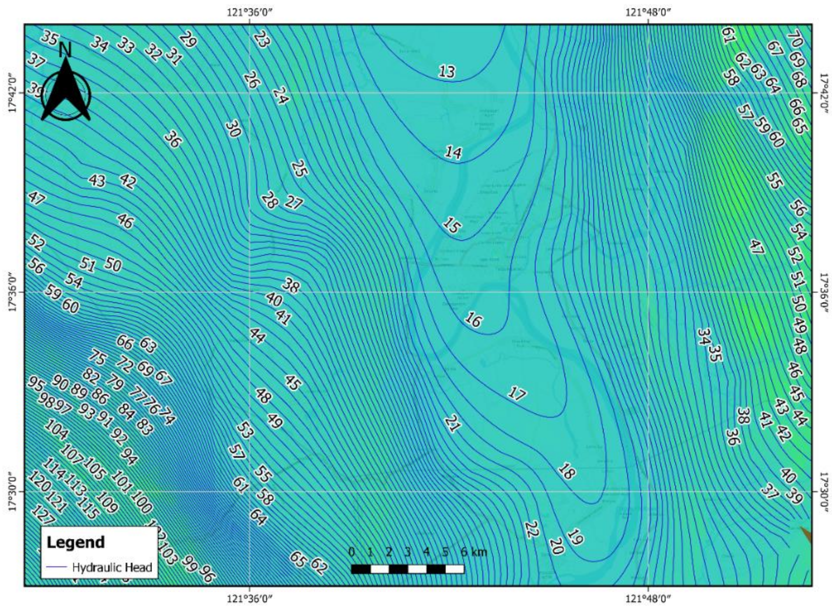


Figure 13. Hydraulic heads in Metropolitan Tuguegarao before groundwater development

3.4 Basin Water Balance

Average daily rainfall in CRB accumulates to 201.90 MCM (or 73,693.5 MCM annually), while the simulated daily recharge is 21.41 MCM (or 7,814.65 MCM annually), as shown in Figure 14. Therefore, it can be inferred that 10.60% of rainfall contributes to recharge based on the modeled system. For comparison, the Department of Environment and Natural Resources (DENR) estimated CRB's average recharge at 10.65% of rainfall [27]. Groundwater recharge from rainfall is 14.30% for Agno River Basin [30], 10.37% for Mindanao River Basin [31], and 2.22% for Buayan-Malungon River Basin [32]. Evapotranspiration and groundwater discharge to rivers through baseflow are the principal outflow components in CRB, with baseflow accounting for 7.30% of rainfall (or 5,384.45 MCM annually).

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  CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
  ------------------                 ------------------------

        IN:                                   IN:
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          STORAGE =           0.0000            STORAGE =           0.0000
    CONSTANT HEAD =           0.0000      CONSTANT HEAD =           0.0000
           RIVERS =           0.0000             RIVERS =           0.0000
               ET =           0.0000                 ET =           0.0000
         RECHARGE =    21411738.0000           RECHARGE =    21411738.0000
  SPECIFIED FLOWS =           0.1560    SPECIFIED FLOWS =           0.1560
  GHOST-NODE FLUX =           0.0000    GHOST-NODE FLUX =           0.0000

         TOTAL IN =    21411738.1560           TOTAL IN =    21411738.1560

       OUT:                                  OUT:
       ----                                  ----
          STORAGE =           0.0000            STORAGE =           0.0000
    CONSTANT HEAD =           0.0000      CONSTANT HEAD =           0.0000
           RIVERS =    14751931.8300             RIVERS =    14751931.8300
               ET =     6659806.3280                 ET =     6659806.3280
         RECHARGE =           0.0000           RECHARGE =           0.0000
  SPECIFIED FLOWS =           0.0000    SPECIFIED FLOWS =           0.0000
  GHOST-NODE FLUX =           0.0000    GHOST-NODE FLUX =           0.0000

        TOTAL OUT =    21411738.1600          TOTAL OUT =    21411738.1600

         IN - OUT =          -0.0040           IN - OUT =          -0.0040

PERCENT DISCREPANCY =          -0.00    PERCENT DISCREPANCY =          -0.00
```

Figure 14. Volumetric budget of the steady-state model (m^3/day)

The simulated water balance for Metropolitan Tuguegarao during May and November 2020 were also presented to describe conditions representative of the usual dry and wet periods, respectively. Table 7 reveals that most water was abstracted through evapotranspiration during the dry period, contributing 50% from the total outflow. A portion of groundwater was still contributed to streams despite low recharge. It was during wet months that baseflow increased due to a higher groundwater supply.

Table 7. Flow budgets within Metropolitan Tuguegarao in 2020

Components	May 2020		November 2020	
	Inflow (m^3)	Outflow (m^3)	Inflow (m^3)	Outflow (m^3)
Wells	—	1,457,719.20	—	1,410,696.00
Baseflow	—	2,877,708.92	—	3,378,786.00
Evapotranspiration	—	4,948,130.10	—	2,182,071.30
Recharge	2,855,894.84	—	4,926,720.00	—
From/To Other Zones	5,215,133.10	476,069.48	5,242,821.00	447,955.20
Total	8,071,027.94	9,759,627.70	10,169,541.00	7,419,508.50
Change in Storage	-1,688,599.76 m^3		2,750,032.50 m^3	

Figure 15 plots the inflows and outflows of the local basin from 2019 to 2021. A total of 6.05 MCM of water recharged the aquifer system from December 2019 to May 2020, while 13.24 MCM from June to November 2020. Within the monsoon period, the amount of rainfall reaches 66% of annual precipitation, indicating groundwater is recharged substantially. The water balance shows the groundwater being recharged seasonally by rainfall while receiving constant lateral flow from the highlands.

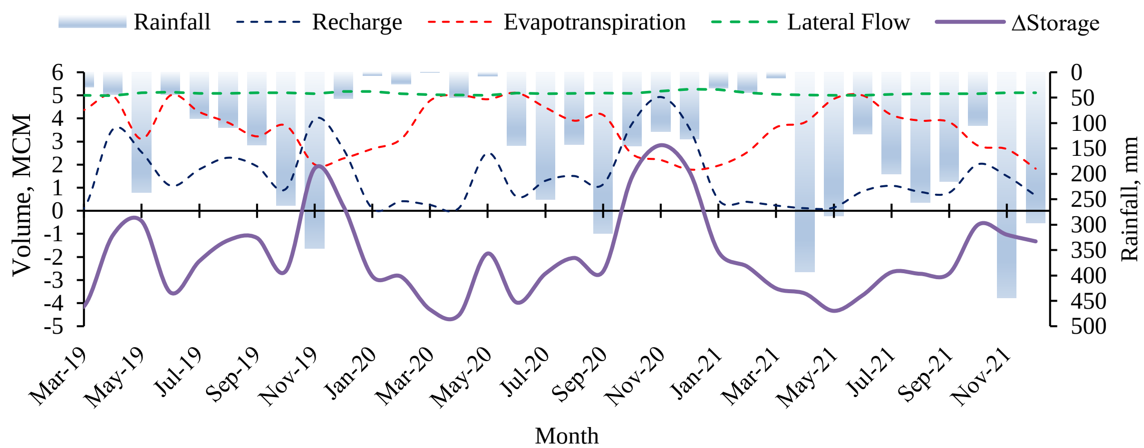

Figure 15. Flow budget from 2019 to 2021

3.5 Baseflow contributes 3.14 MCM to Surface Water

Rivers in the basin are generally effluent in nature as the simulated discharge to water bodies is sustained throughout the year regardless of rainfall seasonality. For instance, Figure 16 shows the continuous baseflow, averaging at 3.14 MCM monthly, from a portion of the Cagayan River in the metropolitan.

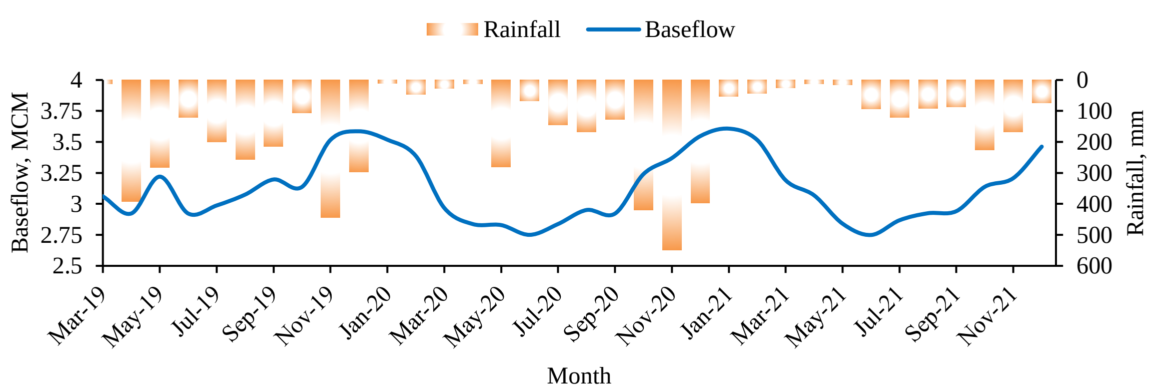

Figure 16. Rainfall-baseflow relationship

Furthermore, Figure 17 illustrates the river–aquifer interaction, which shows a direct relationship between the river stage and groundwater flux from the river boundary. As the outflow from the boundary increases, the river stage also increases, confirming the substantial role of groundwater through baseflow to rivers.

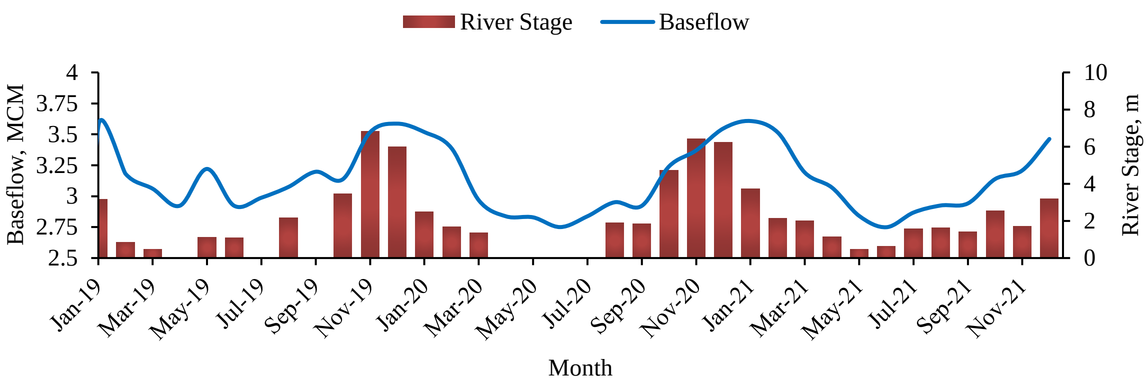

Figure 17. Baseflow-river stage relationship

3.6 Groundwater Production yielded Critical Water Levels

The calibrated model was run to predict groundwater conditions under the strategies discussed in Section 2.4. The simulation results were summarized in Table 8, comparing critical pumping water levels from the simulated water levels. Notably, CAG-TUG-5, CAG-TUG-7, CAG-TUG-13, and CAG-PEN-23, which constitute 31% of the total existing production, exceeded permitted pumping water level under MTWD-1, MTWD-2, and MTWD-3 settings.

Table 8. Comparison of simulated water level (masl) to critical pumping water level (masl)

Station	MTWD -1	MTWD -2	MTWD -3	MTWD -4	MTWD -5	MTWD -6	Critical PWL
CAG-TUG-1	7.12	0.67	6.27	10.65	4.72	10.89	-1.00
CAG-TUG-2	7.39	0.58	6.61	10.78	4.64	11.03	1.00
CAG-TUG-3	7.87	2.40	7.40	10.77	5.78	11.05	3.00
CAG-TUG-5	4.84	2.78	2.60	8.04	4.12	7.66	8.00
CAG-TUG-6	8.82	6.11	7.77	10.49	7.90	10.45	-2.00
CAG-TUG-7	5.30	0.95	4.97	12.58	3.66	12.91	10.00
CAG-TUG-8	7.14	0.65	6.29	10.66	4.71	10.90	0.00
CAG-TUG-9	9.89	5.50	7.09	11.81	7.99	11.31	9.00
CAG-TUG-10	8.00	3.51	1.01	10.51	6.27	9.00	-1.00
CAG-TUG-11	15.23	14.64	15.32	15.41	14.71	15.42	7.00
CAG-TUG-12	8.13	1.87	5.15	11.18	5.60	10.77	2.00
CAG-TUG-13	5.45	1.15	5.13	12.59	3.83	12.97	9.00
CAG-TUG-14	5.70	1.35	5.24	10.41	5.04	10.43	4.00
CAG-TUG-15	7.84	4.83	7.38	10.47	7.23	10.74	3.00
CAG-TUG-16	7.15	2.34	6.69	11.13	4.24	11.43	5.00
CAG-TUG-17	8.50	4.84	3.10	10.67	7.11	9.58	5.00
CAG-PEN-23	22.53	20.58	22.88	24.49	22.25	25.13	25.00

Station	MTWD -1	MTWD -2	MTWD -3	MTWD -4	MTWD -5	MTWD -6	Critical PWL
CAG-PEN-24	21.93	19.50	22.30	24.41	21.60	25.13	20.00
CAG-TUG-147	—	—	10.94	—	—	14.52	—
CAG-TUG-148	—	—	6.78	—	—	11.24	—
CAG-TUG-149	—	—	4.69	—	—	10.28	—

3.7 Groundwater Reduction due to Surface Water Supplies

The proposed MTWD surface water project, which aims to deliver 30 MLD of water, will not only reduce the city's current massive groundwater extraction but will also improve its current supply [26]. The extracted water will be pumped to the steel-bolted tanks currently supplied by CAG-PEN-23 and CAG-PEN-24, which provides water to the city's northeastern barangays. With the facility, groundwater production was estimated to be reduced by up to 63%. In Table 8, there will still be wells at critical levels although the numbers were reduced: from four to one given MTWD-4 scenario, 12 to six under MTWD-5, and to just one for MWTD-6 scenario. Figure 18 shows that water-level recovery in selected wells after the rate reductions. The blue line indicates the pre-pumping level, the red line represents the previously simulated level, and the green line reflects the water level if rates are reduced.

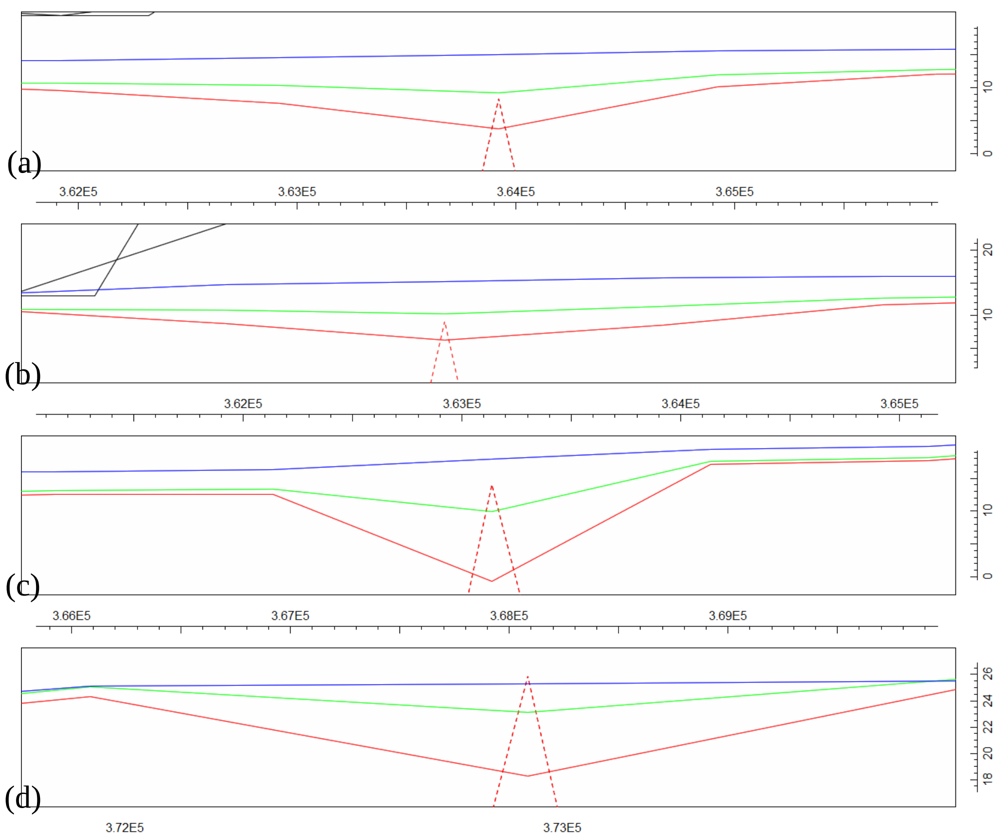

Figure 18. Water-level recovery due to MWTD-4 scenario for (a) CAG-TUG-14, (b) CAG-TUG-3, (c) CAG-TUG-13, and (d) CAG-PEN-23

As baseline, the simulated wellfield drawdowns in 2050 are illustrated from Figure 19 to Figure 21.

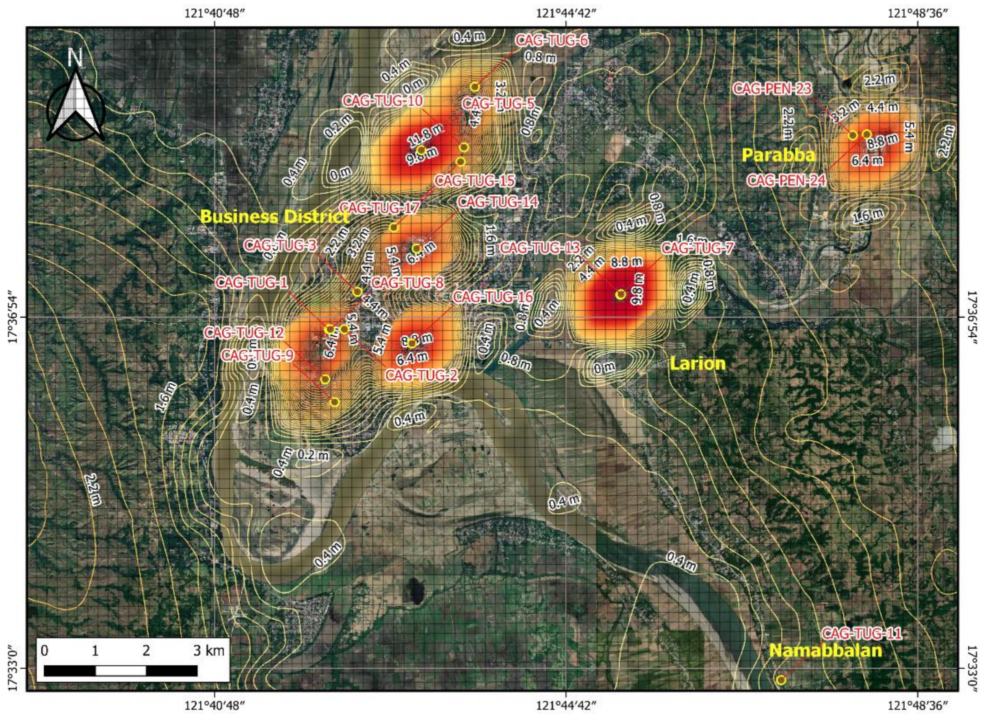

Figure 19. 2050 drawdown map considering MTWD-1 scenario

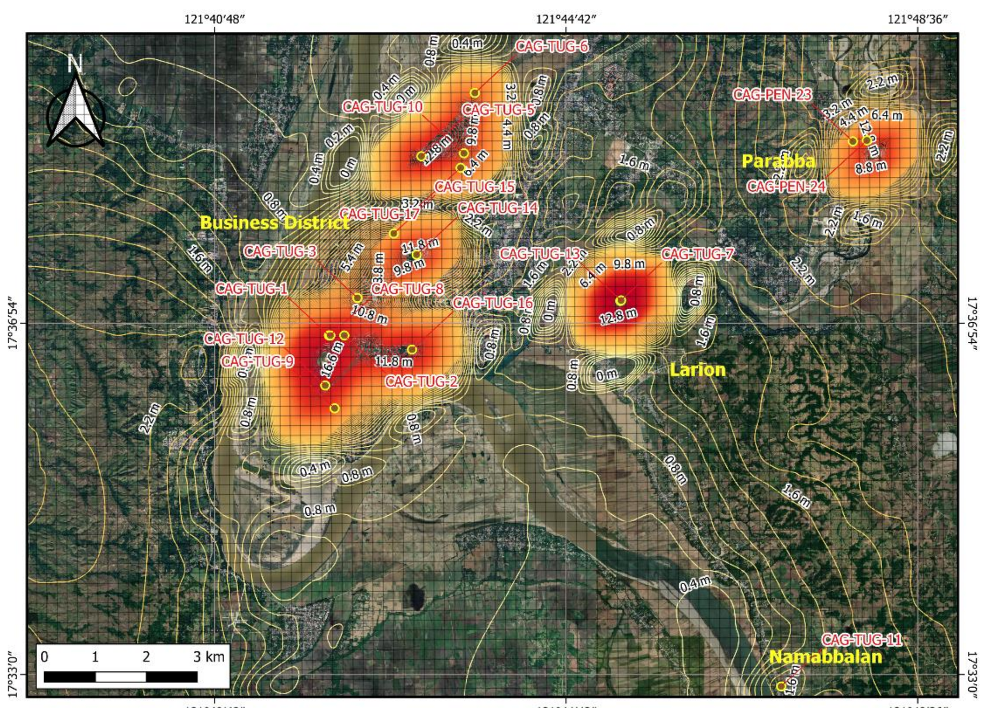

Figure 20. 2050 drawdown map considering MTWD-2 scenario

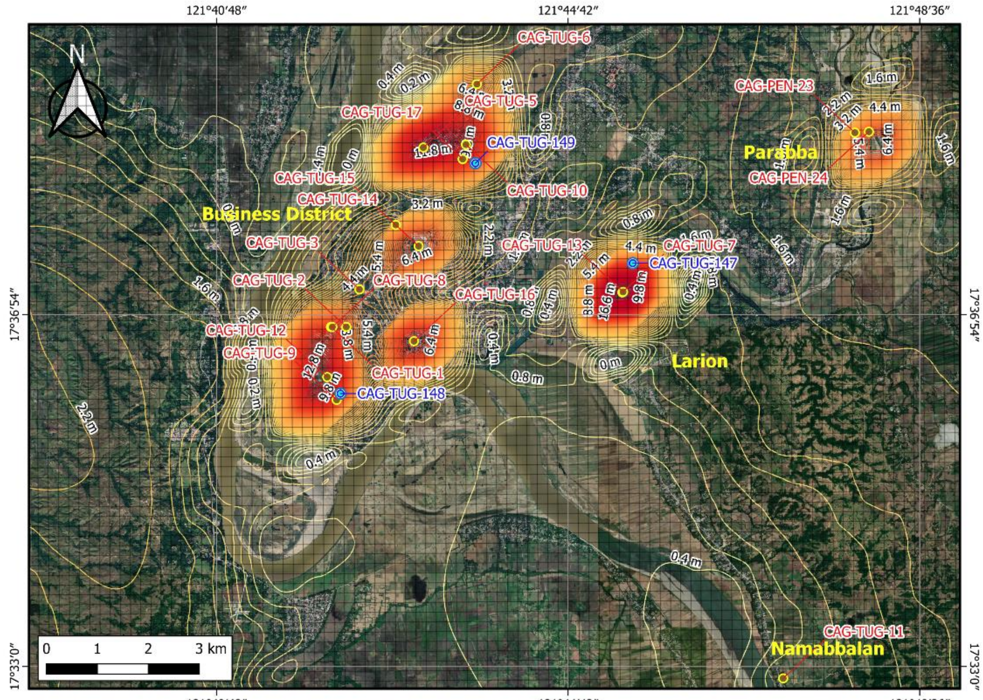

Figure 21. 2050 drawdown map considering MTWD-3 scenario (blue points indicate proposed well)

IV. CONCLUSIONS AND RECOMMENDATIONS

This research utilized numerical hydraulic analysis to assess groundwater sustainability in Metropolitan Tuguegarao, the largest resource consumer in Northern Luzon. A groundwater model enabled recharge estimation and flow simulation to describe the spatiotemporal distribution of groundwater levels. The findings aim to contribute to the existing body of knowledge by providing a more comprehensive assessment of groundwater resources in one of the country’s key basins.

A four-layer flow model was created for the Cagayan Valley Aquifer System, with the layering of formations investigated using MGB geologic maps. Because no groundwater flow simulations were performed in the area, this study provides the first conceptual and numerical models for Metropolitan Tuguegarao. This also meant having no prior knowledge of the boundary conditions required by the modeling process. As a result, the main area was evaluated using MODFLOW-LGR to define the local boundary conditions from the regional grid. The numerical model was calibrated, validated, and scenario analyses were performed to assess resource sustainability in the local domain.

The findings of this research on all model scenarios indicate that groundwater levels will decrease in the coming years, with four wells (i.e., CAG-TUG-5, CAG-TUG-7, CAG-TUG-13, and CAG-PEN-23) below critical levels. The simulated drawdowns are extensive since the wells are clustered. However, with the proposed surface water facility, groundwater production may be reduced, allowing water level recovery. With groundwater perennially discharging to rivers regardless of rainfall seasonality, surface water is sustained.

Based on these findings, simple but practical management recommendations may be adhered to for more efficient resource use. Watershed protection will undoubtedly help preserve natural recharge. Because the model can return the basin water balance, alterations in recharge zones can be investigated to estimate recharge rates. The model also can locate piezometric depressions by simulating extraction from proposed sites. Proper well positioning will prevent well interference and perennial overdrafts, considering the clustered location of existing wells. Since groundwater contributes to surface water continuously, conjunctive use between resources may be considered. Optimal water allocation, incorporating various pumping strategies, can be determined through the model's hydrologic and hydraulic output. Overall, the effective planning, operations, and management by the MTWD will remain crucial toward initiatives that promote sustainable water use, the rehabilitation of existing sources, and the development of new facilities.

Finally, this research initiates the call for more accurate modelling database that involve extensive field data collection. It will be advantageous for water districts and private well owners to regularly monitor and record water levels and water quality parameters [20]. Pumping tests must be carried out as this will allow the definition of more hydrogeologic parameters within the basin. As this is research is the first of its kind in the area, major adjustments can be integrated to the model when new information becomes available. It will also be helpful to assess the impacts of other factors such as land use, land cover, and policy intervention on resource utilization.

V. ACKNOWLEDGEMENTS

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