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Combined Adaptation to Land Cover Change and Global Warming for the Optimization of Cascade Reservoir Operation in the Upper Sekampung Watershed

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ABSTRACT: Optimizing the operation of a cascade reservoir system requires a single adaptation-ready series of dependable discharge, yet land cover change and global warming are typically assessed separately and are rarely combined into one hydrological input ready for optimization. This study integrates two previously derived adaptation drivers for the Batutegi-Way Sekampung cascade system in the Upper Sekampung Watershed, Lampung Province, Indonesia: (i) the monthly runoff change factor due to land cover (2014-2024, SCS Curve Number method), and (ii) the delta-change-based percentage shift in dependable discharge due to temperature under four incremental temperature-rise scenarios (+0.5 to +2.0 degrees C), both applied multiplicatively to the same measurement-based historical Q80/Q50/Q20 baseline. Because two independent measures of warming actually observed in this watershed - a bi-period comparison (+0.425 degrees C) and a projected trend change to the present (+0.520 degrees C) - both identify the +0.5 degree C scenario as the one most representative of current conditions, the combined "2024 Land Cover + Temperature +0.5 degrees C" scenario is recommended as the primary adaptation-ready dependable discharge input for short-term cascade reservoir operation optimization under a non-linear programming (NLP) framework, while the combined +1.0 to +2.0 degree C scenarios are retained as medium- to long-term sensitivity cases. Under the recommended combined scenario, the mean annual Q50 is 19.93 m3/s at Batutegi and 23.63 m3/s at Way Sekampung, each within about 0.3% of the value due to land cover alone, indicating that the land cover change signal currently dominates over the temperature signal in this watershed, even though both drivers act in the same qualitative direction at Way Sekampung and in the same direction at Batutegi, where the temperature effect only partially offsets the land-cover-driven increase. The resulting monthly Q80/Q50/Q20 series are presented as a ready-to-use input table for NLP-based cascade reservoir operation optimization in the next stage of this research.

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1. INTRODUCTION

Cascade reservoir systems are operated jointly to balance several often-competing objectives - irrigation supply, raw water supply, hydropower generation, and flood control [25] - which are typically formulated as a non-linear programming (NLP) optimization problem constrained by the dependable inflow available to each reservoir within the cascade system, as widely applied in numerous studies of cascade reservoir and irrigation operation optimization based on mathematical programming [3,4,5,10]. There is precedent for this kind of scenario-based climate adaptation planning in Lampung Province, including a recent cost-benefit study of reforestation as a disease-risk adaptation measure under global warming scenarios [26], as well as updates to cascade reservoir operating rules for adapting to climate change that have been applied in various other watersheds [3,6], including agroforestry-based climate change mitigation directly assessed in the Batutegi Protection Forest, Lampung [17], which underscores the broader relevance of explicit adaptation scenarios in this region. The Batutegi and Way Sekampung Dams in the Upper Sekampung Watershed, Lampung Province, Sumatra, Indonesia, form such a cascade system. The reliability of any NLP-based operating pattern derived for this cascade system depends directly on the reliability of the Q80/Q50/Q20 dependable discharge series used as its hydrological input.

Two earlier analysis stages of this research separately measured two drivers of change in dependable discharge in this watershed that are relevant to adaptation: land cover change between 2014 and 2024, using the SCS Curve Number method following an approach validated in the literature [1], and global warming, using recalculated Penman-Monteith-based evapotranspiration combined with delta-change scenario analysis [2] on a reconstructed monthly water balance model. Because both drivers were derived from, and applied multiplicatively to, the same historical baseline (this study's primary data, the Q80/Q50/Q20 series in Tables 25/26), they can be combined directly into a single adaptation-ready dependable discharge series, which is the objective of this study.

This study therefore (i) combines the land-cover- and temperature-driven adaptation factors multiplicatively for the Batutegi and Way Sekampung ("Total Natural") series under the four warming scenarios; (ii) identifies, based on the observed warming benchmark established in this study's temperature analysis stage, which combined scenario best represents current conditions and should be used as the primary NLP input; and (iii) presents the resulting monthly Q80/Q50/Q20 series as a ready-to-use hydrological input table for cascade reservoir operation optimization.

2. MATERIALS AND METHODS

2.1 Study area and baseline data

The Upper Sekampung Watershed comprises the catchment area of the Batutegi Dam and the incremental catchment area of Way Sekampung downstream of it, which together form a cascade system in southern Lampung Province, Sumatra, a region that has also been the focus of various land and water conservation studies in tropical agricultural watersheds [18]. The pre-adaptation baseline used throughout this study is the measurement-based historical Q80/Q50/Q20 dependable discharge series for Batutegi and for the Way Sekampung "Total Natural" basis (combined Batutegi outflow and incremental inflow), derived using the Weibull plotting position method as this study's primary data (Tables 25-26), following the flow duration curve analysis framework commonly used in dependable discharge studies [8].

Figures 1-4 present the official land cover maps of the Ministry of Environment and Forestry (KLHK) for both sub-watersheds for 2014 and 2024, the source basis of the land cover adaptation factor (Section 2.2) combined in this study with the temperature adaptation factor (Section 2.3), following a watershed hydrological modelling approach based on land cover and rainfall data that has also been applied in various other tropical watersheds [13,19].

Figure 1. Land cover map of the Batutegi Dam catchment area, 2014. Source: KLHK, SIMONTANA web portal [21].

Figure 2. Land cover map of the Batutegi Dam catchment area, 2024. Source: KLHK, SIMONTANA web portal [21].

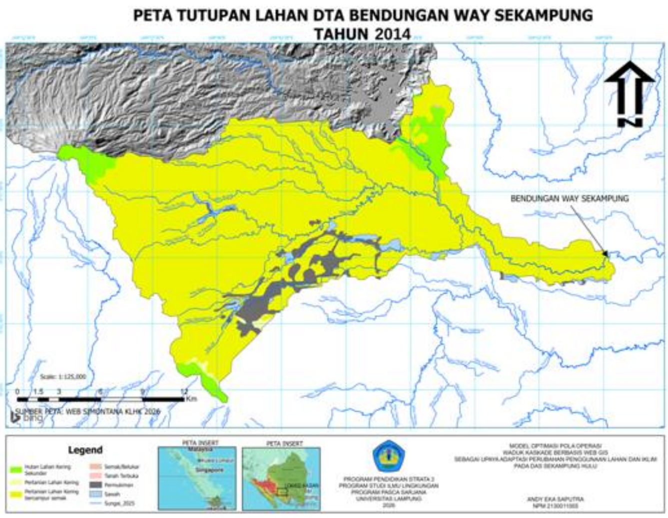

Figure 3. Land cover map of the Way Sekampung Dam catchment area, 2014. Source: KLHK, SIMONTANA web portal [21].

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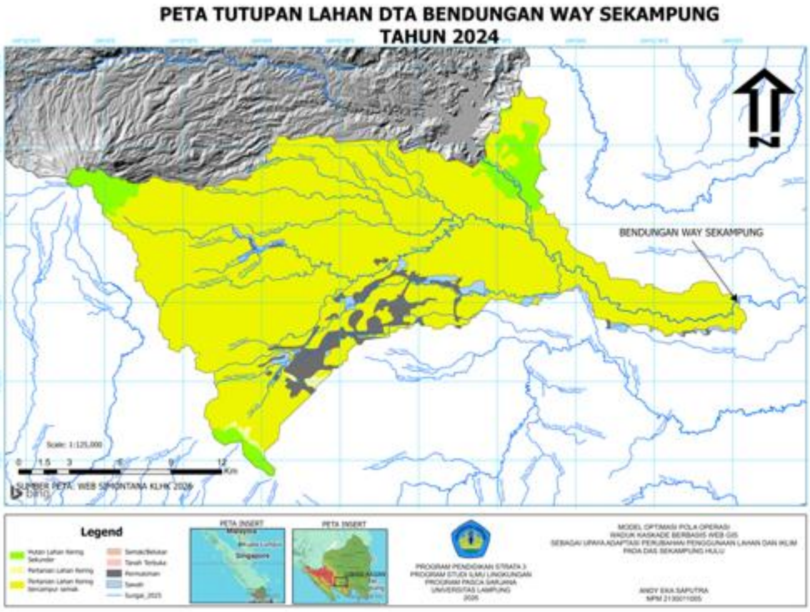

Figure 4. Land cover map of the Way Sekampung Dam catchment area, 2024. Source: KLHK, SIMONTANA web portal [21].

2.2 Land cover adaptation factor

The monthly runoff change factor due to land cover for the 2014-2024 period was derived using the SCS-CN method [22], following an approach validated in similar land cover change studies [1,9,11,12,20], applied as a ratio (2024 land cover CN versus 2014 land cover CN, identical rainfall input) for the Batutegi sub-watershed and the Way Sekampung incremental sub-watershed, as part of this study's earlier analysis stage. For the Way Sekampung Total Natural basis, a volume-weighted combined factor merging the Batutegi factor and the incremental catchment factor was used, as detailed in that analysis stage, following a remote-sensing-based land cover change assessment framework also applied in other tropical watersheds [14].

2.3 Temperature adaptation factor

The percentage shift in dependable discharge due to temperature, for four incremental temperature-rise scenarios (+0.5, +1.0, +1.5, +2.0 degrees C), was derived using the delta-change method [2], as widely applied in studies of climate change impacts on river discharge in the tropical Southeast Asian region [7,15,16], applied to a reconstructed monthly water balance model following the validated F.J. Mock method [24], with reference evapotranspiration recalculated using the FAO-56 Penman-Monteith method [23], as part of this study's earlier analysis stage. That analysis stage also established, from two independent measures of temperature change actually observed in this watershed (a bi-period comparison and a projected trend change to the current year), that the +0.5 degree C scenario best represents current conditions and constitutes the recommended short-term benchmark.

2.4 Combined adaptation-ready dependable discharge

Both adaptation factors were combined multiplicatively from the same historical baseline for each sub-watershed, percentile, and month:

Q_final(p, month, dt) = Q_historical(p, month) × f_landcover(month) × [1 + DeltaTemperature(p, month, dt)]

This multiplicative combination assumes that the two adaptation drivers act independently, i.e., no explicit land × temperature interaction is simulated within a single combined physical model; this is documented as a methodological assumption (see Section 3.4).

The combination was carried out for all four warming scenarios (dt = 0.5, 1.0, 1.5, 2.0 degrees C) plus the land-cover-only baseline (dt = 0), for Batutegi and Way Sekampung Total Natural, and for each of the Q80, Q50, and Q20 percentiles, yielding one complete monthly series for each scenario.

3. RESULTS AND DISCUSSION

3.1 Combined dependable discharge under various scenarios

Table 1 and Table 2 summarize the mean annual Q80/Q50/Q20 dependable discharge for Batutegi and Way Sekampung, respectively, under the land-cover-only baseline and the four combined land-plus-temperature scenarios. The combined +0.5 degree C scenario (marked with an asterisk) is the recommended primary scenario, identified in this study's temperature analysis stage as the one closest to the temperature change actually observed in this watershed to date.

Batutegi, mean annual dependable discharge by scenario:

Scenario	Q80 (m3/s)	Q50 (m3/s)	Q20 (m3/s)
2024 Land Cover only (dt=0, baseline)	14.23	19.99	27.72
2024 Land Cover + Temperature +0.5 degree C *	**14.14**	**19.93**	**27.61**
2024 Land Cover + Temperature +1.0 degree C	14.06	19.86	27.51
2024 Land Cover + Temperature +1.5 degree C	13.98	19.80	27.41
2024 Land Cover + Temperature +2.0 degree C	13.90	19.73	27.32

Table 1. Mean annual Q80/Q50/Q20 dependable discharge at Batutegi, land-cover-only baseline versus the four combined land-plus-temperature scenarios. * = primary scenario recommended for short-term NLP optimization.

Way Sekampung (Total Natural), mean annual dependable discharge by scenario:

Scenario	Q80 (m3/s)	Q50 (m3/s)	Q20 (m3/s)
2024 Land Cover only (dt=0, baseline)	16.83	23.65	35.40
2024 Land Cover + Temperature +0.5 degree C *	**16.76**	**23.63**	**35.25**
2024 Land Cover + Temperature +1.0 degree C	16.69	23.58	35.12
2024 Land Cover + Temperature +1.5 degree C	16.62	23.53	34.98
2024 Land Cover + Temperature +2.0 degree C	16.56	23.47	34.85

Table 2. Mean annual Q80/Q50/Q20 dependable discharge at Way Sekampung (Total Natural), land-cover-only baseline versus the four combined land-plus-temperature scenarios. * = primary scenario recommended for short-term NLP optimization.

Across all scenarios, the temperature effect only partially offsets the land-cover-driven increase and does not reverse its sign: mean annual Q50 declines only slightly, from 19.99 m3/s (land cover only) to 19.73 m3/s (combined +2.0 degrees C) at Batutegi, and from 23.65 m3/s to 23.47 m3/s at Way Sekampung, across the full range of warming scenarios assessed. This shows that, for this watershed and within the range of scenarios assessed, land cover change is currently the dominant adaptation driver, with global warming acting as a smaller secondary modifier.

3.2 Recommended input series for NLP optimization

Table 3 and Table 4 present the full monthly Q80/Q50/Q20 series under the recommended combined "2024 Land Cover + Temperature +0.5 degree C" scenario, for Batutegi and Way Sekampung, respectively. This series is proposed as a direct hydrological input (inflow boundary condition) for the next stage of this research: non-linear programming (NLP)-based optimization of the combined Batutegi-Way Sekampung cascade operating pattern, with Q20 representing wet-condition inflow, Q50 representing normal-condition inflow, and Q80 representing dry (critical) condition inflow.

Batutegi, recommended combined scenario (2024 Land Cover + Temperature +0.5 degree C), m3/s:

Percentile	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Q80 FINAL (for NLP)	18.44	24.33	20.02	23.81	17.25	14.29	9.31	6.95	6.30	4.87	8.14	16.02
Q50 FINAL (for NLP)	23.42	33.23	34.59	28.23	22.11	17.92	13.56	10.31	8.40	8.93	15.83	22.63
Q20 FINAL (for NLP)	29.58	40.63	41.75	40.01	32.01	23.69	18.73	18.29	16.04	17.04	24.79	28.80

Table 3. Batutegi Q80/Q50/Q20, recommended combined adaptation scenario, monthly. Mean annual values: Q80=14.14, Q50=19.93, Q20=27.61 m3/s.

Way Sekampung (Total Natural), recommended combined scenario (2024 Land Cover + Temperature +0.5 degree C), m3/s:

Percentile	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Q80 FINAL (for NLP)	20.74	37.92	36.81	29.63	23.11	15.78	11.14	8.10	6.03	4.14	3.59	4.15
Q50 FINAL (for NLP)	32.35	47.17	42.42	39.19	31.60	24.37	15.84	11.66	8.67	5.97	5.85	18.44
Q20 FINAL (for NLP)	49.91	56.22	51.78	46.26	50.29	34.69	25.26	20.54	12.77	18.63	19.27	37.40

Table 4. Way Sekampung (Total Natural) Q80/Q50/Q20, recommended combined adaptation scenario, monthly. Mean annual values: Q80=16.76, Q50=23.63, Q20=35.25 m3/s.

3.3 Implications for cascade reservoir operation optimization

The combined series in Tables 3-4 provide an internally consistent set of inflow boundary conditions - simultaneously adjusted for observed land cover change and the best available estimate of current warming - for formulating the NLP problem for Batutegi-Way Sekampung cascade operation. Because the combined +1.0, +1.5, and +2.0 degree C scenarios (Tables 1-2) remain available alongside the recommended +0.5 degree C scenario, the same NLP formulation can also be re-run under these more extreme scenarios as a sensitivity study or for long-term planning, without requiring the hydrological derivation to be redone from scratch.

3.4 Limitations

The multiplicative combination of the two adaptation drivers (Section 2.4) assumes that their effects are independent; no single combined physical land-by-climate model was run to test the effect of their interaction, and this remains a direction for future research. The land cover factor for the Way Sekampung Total Natural basis relies on a volume-weighted approach rather than a directly published value, and the percentage shift due to temperature was carried over from a reconstructed water balance model with a known absolute bias derived through the delta-change method [2]. Both limitations were discussed transparently in this study's earlier analysis stages and are inherited here.

4. CONCLUSION

Combining the land cover change and global warming adaptation drivers derived in this study's two earlier analysis stages yields a single adaptation-ready Q80/Q50/Q20 dependable discharge series for the Batutegi and Way Sekampung Dams operating as a cascade in the Upper Sekampung Watershed. Land cover change (2014-2024) is currently the dominant driver of change in dependable discharge in this watershed, with global warming acting as a smaller secondary and partially offsetting modifier across the range of scenarios assessed (+0.5 to +2.0 degrees C). Based on two independent measures of temperature change actually observed, the combined "2024 Land Cover + Temperature +0.5 degree C" scenario is recommended as the primary hydrological input for short-term cascade reservoir operation optimization under a non-linear programming framework, with the more extreme combined scenarios retained for medium- to long-term sensitivity planning. Future research should extend this combined framework with a coupled land-by-climate hydrological model and incorporate the resulting series directly into the cascade NLP optimization formulation.

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