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An Integrated Budget Calculation Model for Environmental Geological Mapping

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ABSTRACT

As a cornerstone of national geological endeavors, environmental geological mapping requires scientifically rigorous budgeting standards to enhance resource allocation efficiency and ensure survey quality. This study establishes a multidimensional budget calculation model tailored for 1:50,000 environmental geological mapping, integrating the cost-quota theory, which links resource inputs to standardized work units, within a structured four-phase methodology comprising data collection, quota determination, model development, and empirical validation. We extracted key productivity metrics—such as work efficiency (e.g., a standardized group-day efficiency of 4.8 km²/day), personnel deployment, material consumption, equipment allocation, and transportation quotas—from 12,843 field logs provided by 16 national survey teams. The model applies fundamental engineering economics principles ("quantity–price–cost") underpinned by cost-quota theory to compute theoretical budget values, which are further refined through a dual-dimensional adjustment mechanism incorporating geological complexity (coefficients ranging from 1.0 to 1.5) and regional cost coefficients. Empirical validation shows that the proposed model reduces budget deviations to below 3% (specifically 2.1%, 1.7%, and 2.5% across three distinct geological settings), markedly surpassing traditional budgeting approaches. This study offers a scalable and scientifically grounded framework for budget management in geological surveys, with substantial practical implications for optimizing fiscal resource allocation and promoting standardization within the industry..

Keywords: environmental geological mapping; budget standard; quota calculation; cost model

Introduction

Environmental geology, an interdisciplinary field integrating environmental science and geological studies, examines the interactions between human activities and the geological environment [1,2]. As a core component of this discipline, environmental geological mapping employs systematic observation and mapping to assess the impacts of geological hazards—such as landslides, debris flows, land subsidence, and water contamination—on human production, daily life, and infrastructure [3,4]. Understanding and predicting water contamination, a pervasive environmental geological hazard, requires deep insights into subsurface processes. These include contaminant transport in porous media [5,6] and the hydrological dynamics of complex systems like karst aquifers [7,8]. In recent years, these surveys have become indispensable for evidence-based resilient urban planning and sustainable resource management [9].

The execution of mapping projects relies heavily on robust and scientifically sound budgetary frameworks for effective resource allocation and project success [10,11]. Internationally, methodologies for geological survey cost estimation have evolved to incorporate factors such as geological complexity, terrain, and technological inputs. For example, hierarchical systems and regression models integrating environmental variables have been developed to enhance budgetary accuracy and adaptability [12,13]. In China, researchers have proposed adjustments for intellectual labor valuation and macroeconomic factors to refine cost standards [14,15]. Despite these advances, a significant gap persists: existing budgetary research and standards remain generalized, lacking a dedicated, systematic model tailored to the unique operational and cost structures of environmental geological mapping. This gap is exacerbated because China’s core geological survey budget quota system, last revised in 2009 [16,17], has not kept pace with technological advancements (e.g., the widespread use of drones and portable analyzers) or profound socioeconomic changes (e.g., rising labor costs and institutional reforms) [18,19]. Consequently, current standards often fail to reflect actual survey costs, leading to budget shortfalls, inefficient fund use, and impediments to project planning and fiscal control.

Addressing this budgetary standard gap is urgent. Scientifically valid cost estimation is fundamental for the efficient execution of environmental geological mapping, which underpins critical national initiatives in territorial spatial planning and ecological conservation [20]. A primary obstacle lies in obtaining reliable, grassroots "basic quota" data—the elemental time and cost metrics for field activities—following the dissolution of traditional data collection channels due to institutional reforms [21].

Therefore, this study aims to construct and validate a novel, multidimensional budget calculation model specifically designed for environmental geological mapping, thereby bridging the gap between outdated generic standards and contemporary project realities. To achieve this aim, the study pursues three specific objectives: (1) to introduce and demonstrate a novel method for collecting basic field-level quotas via operational log mining; (2) to establish a dedicated cost estimation model using an activity-based costing framework; and (3) to empirically validate the model and provide a scientific basis for fiscal budgeting, contributing to the interdisciplinary field of geological economics.

Methods

This study integrates case study analysis, cost decomposition, and quota measurement to develop budgetary standards for environmental geological mapping projects (Figure 1).

(1) Data Collection and Processing.

We selected sixteen representative projects (2020–2024) across 16 Chinese provinces. Raw field logs were collected using a standardized template and processed in three stages: (a) Processing: Log entries were codified into quantitative metrics (person-days, equipment-hours). (b) Validation: Internal consistency checks and manager verification resolved anomalies. (c) Aggregation: Validated data were aggregated per project and linked to characteristics such as terrain and scale.

(2) Cost Decomposition and Quota Measurement.

A standardized cost model categorized expenses into direct, indirect, and administrative costs [22,23], following activity-based costing (ABC) principles. Direct costs were parametrically calculated for four modules: Labor, Equipment, Materials, and Transportation [24,25]. A "quantity–price–cost" quota model was then developed: (a) Quantity: Time-motion analysis of processed data yielded standard time quotas per task. (b) Price: Unit costs (labor, materials, etc.) were aggregated and smoothed using a moving average. (c) Cost: Standard rates for indirect and administrative costs were set according to industry-adapted accounting standards, integrating quantities and prices to form theoretical budgetary standards [26,27].

(3) Adjustment Coefficients for Geological Complexity and Regional Factors.

To enhance the applicability of the budgetary standards across diverse field conditions and regions, we applied two sets of adjustment coefficients: (a) Geological Complexity Coefficients (Table 7): Project areas were classified into three grades (Simple, Moderate, Complex) based on a structured expert assessment of terrain roughness, geological structure, hydrogeological conditions, and vegetation cover. The corresponding cost adjustment coefficients were derived by calculating the average normalized cost multiplier observed from the decomposed cost data of projects within each grade. (b) Regional Adjustment Coefficients[28]: To account for broader socio-economic and environmental disparities across provinces, this study adopted a set of pre-established regional adjustment coefficients (see Appendix A). These coefficients, derived from a separate multi-criteria decision analysis (which employed methods such as the Entropy Weight-TOPSIS model to comprehensively weigh factors like regional price indices and average salary levels), were applied directly to calibrate the baseline standards.

(4) Integrated Framework.

The above methods form a coherent analytical pathway from empirical data collection to cost modeling and standard formulation. The framework incorporates both project-specific (complexity) and macro-level (regional) adjustments to enhance the practical applicability of the resulting budgetary standards.

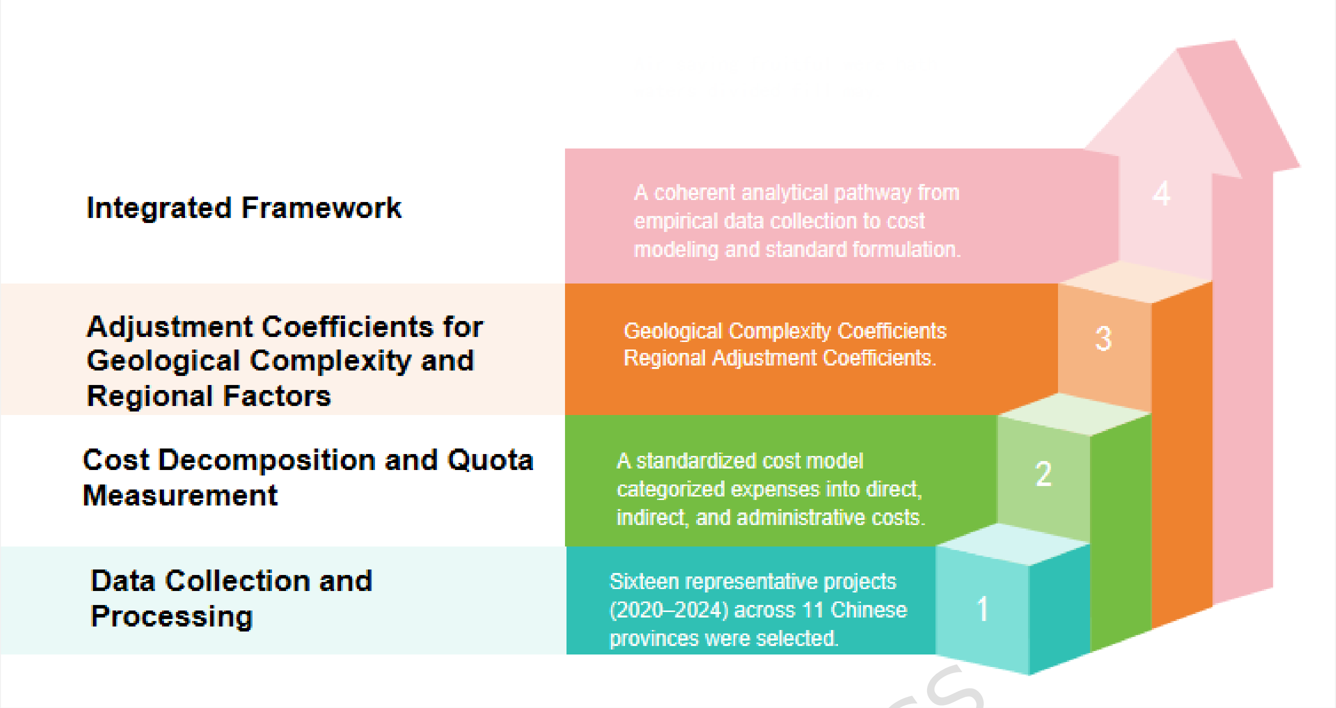

Figure 1. Schematic diagram of the research framework for developing budget standards for environmental geological mapping

Results

This study establishes a budget standard for environmental geological mapping, defined as the benchmark for resource inputs and consumption required to complete one unit of survey work under specific technical conditions. This standard is quantitatively derived by integrating core factors such as personnel allocation, equipment configuration, material consumption, and production efficiency. Its primary function is to effectively link project tasks with financial expenditures, serving as a key reference for evaluating the reasonableness and equity of project budget allocations [29,30]. The theoretical value model of the budget standard is illustrated in Figure 2. The following sections detail the calculation methods for key components—including basic quotas and economic parameters—and provide a comprehensive analysis of the theoretical value estimation process.

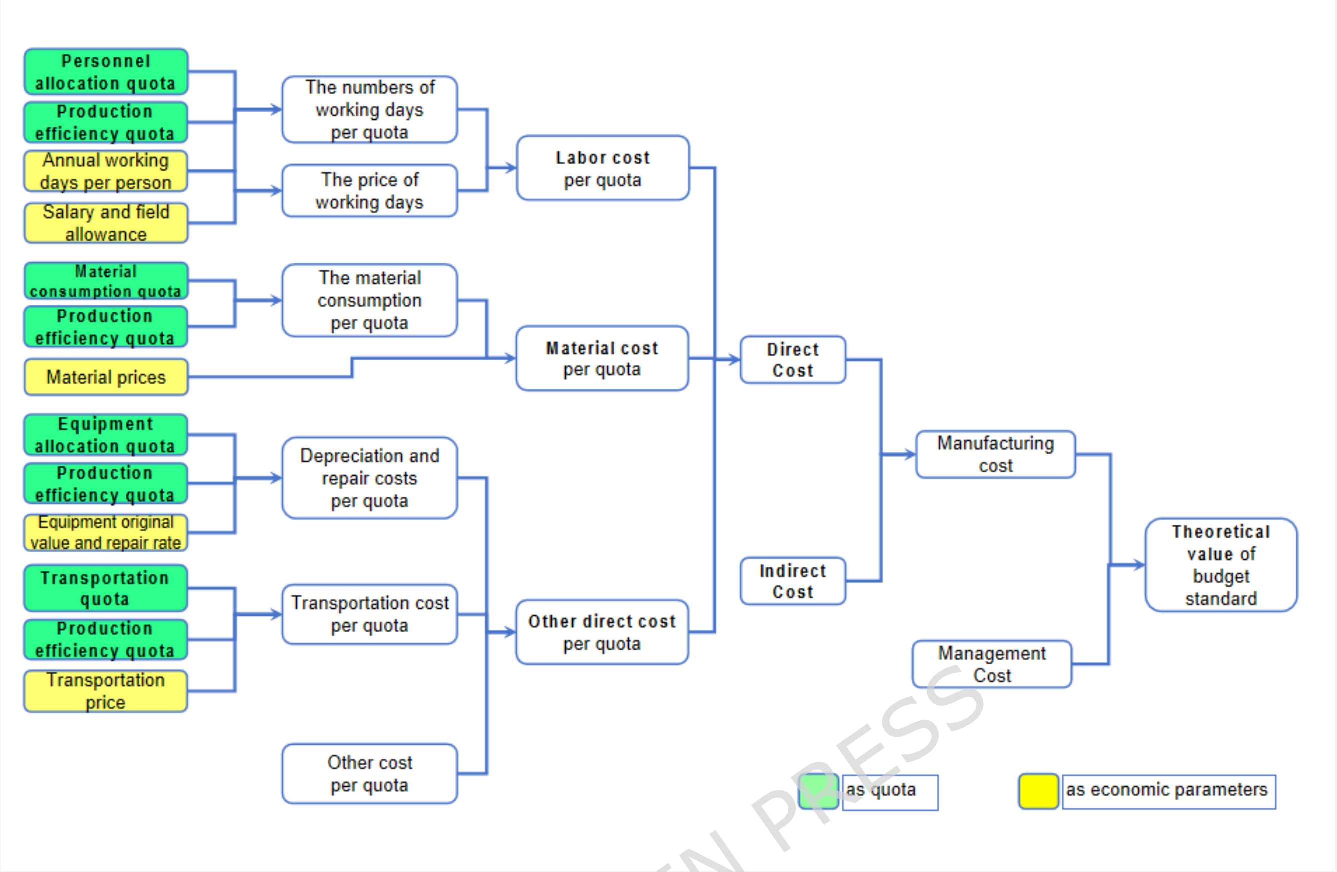

Figure 2 Theoretical value model diagram of budget standards for 1:50,000 environmental geological mapping

(1) Data Preparation and Processing

Prior to analysis, raw field log records from 16 environmental geological mapping projects (Figure 3), totaling 12,843 entries, underwent systematic cleaning, standardization, and aggregation to ensure consistency, accuracy, and reproducibility.

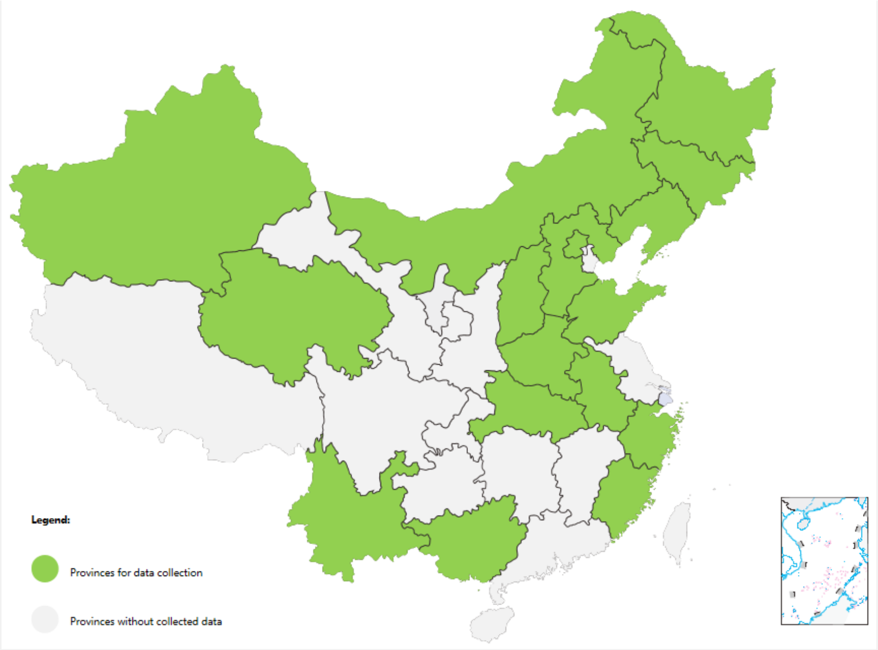

Figure 3. Schematic map illustrating the geographical distribution of the 16 environmental geological mapping projects across China used in this study

Note: Based on the standard map service website GS (2024) 0650 of the Ministry of Natural Resources[31], the base map boundary has not been modified.

①Data Cleaning

Missing Values: Entries with incomplete core fields (e.g., missing dates, location codes, or work method descriptions) were flagged. For critical numerical fields (e.g., calendar days, workload area), missing values were imputed using the median value from records of the same project and work method. Purely descriptive fields with >50% missing data were excluded from quantitative analysis.

Outlier Detection: Values for "Field Calendar Days" and "Annual Workload Area" beyond three standard deviations from the project-specific mean were visually inspected using box plots. Outliers attributable to data entry errors (e.g., misplaced decimal points, unit inconsistencies) were corrected or removed. Outliers representing genuine extreme cases (e.g., exceptionally long fieldwork in remote regions) were retained but noted.

Format Standardization: All date entries were converted to the standardized YYYY-MM-DD format. Location names were mapped to official provincial administrative codes. Work method descriptions were categorized into a controlled vocabulary: "1:50,000 Environmental Geological Mapping," "Other Field Work," and "Indoor Work Time."

②Data Standardization

Time Unit Normalization: Field time was standardized to "calendar days," defined as any day with recorded field activity. Days with logged hours exceeding 8 were prorated (e.g., 12 hours = 1.5 calendar days). Days with fewer than 8 hours were counted as one full calendar day, aligning with industry reporting conventions. Variable Calculation: Derived variables were created consistently:

Total Annual Field Calendar Days per project: Sum of all standardized calendar days from departure to return.

Non-productive Calendar Days: Sum of days explicitly logged under "adverse weather" or "indoor data processing."

Field Time Utilization Structure (%) for a work method: (Σ Field calendar days for the work item / Total annual field calendar days) × 100%.

Allocated Non-productive Days: Calculated using the formula: Non-productive calendar days × [Field calendar days for a specific work method / (Total annual field calendar days − Non-productive calendar days)].

Standard Field Quota Days: Actual calendar working days + Allocated non-productive days.

Group-day Efficiency (km^2 /day): Annual workload area / (Standard Field Quota Days × Number of project teams).

③Data Aggregation

Cleaned and standardized records were aggregated first at the project-work method level to calculate intermediate metrics (e.g., average calendar days, total workload). These project-level summaries were then aggregated to the provincial level for comparative analysis, resulting in the final statistical matrix (Table 1). This rigorous data processing framework ensured a high-quality, consistent dataset as the foundation for all subsequent quota calculations and analyses.

(2) Expert Panel Selection and Delphi Process

To determine key parameters requiring expert judgment (notably, the daily field allowance standard), we employed a structured Delphi method. The expert panel was convened with the following selection criteria:

Professional Expertise: All members possess senior professional titles (Professor or Senior Engineer) and have over 15 years of direct experience in environmental geological survey project management or budgeting.

Institutional Representation: The panel comprised 12 experts selected from three key stakeholder groups: four from the China Geological Survey (funding and policy bodies), four from provincial geological survey institutes (practitioners), and four from leading research universities (academic perspective).

Geographical Coverage: Experts were drawn from six different provinces across eastern, central, and western China to incorporate regional operational perspectives.

The Delphi process consisted of three anonymous questionnaire rounds conducted via a secure online platform. In the first round, experts proposed initial values and justifications for the field allowance. In subsequent rounds, they received anonymized summaries of the group’s responses and reasoning and were asked to revise their estimates. Consensus was defined as achieving a coefficient of variation (CV) of less than 15% for the recommended allowance value. The process converged after three rounds, resulting in the endorsed standard of 80 RMB/person-day for reconnaissance surveys, as reported in the Field Allowance section.

(3) Basic Quota Calculation

① Productivity

This study develops a quantitative evaluation method for production efficiency within the geological survey sector to enhance the scientific basis for resource allocation and the accuracy of management decisions. Based on the processed field logs from 16 environmental geological mapping projects, we constructed a time utilization structure model to systematically analyze the temporal allocation and efficiency of various field operations. A hierarchical approach decomposed field working time as follows:

Analysis of Basic Time Proportion: Field time utilization structure (%) = Σ (field calendar days per work item) / Total annual field calendar days × 100%.

Allocation of Non-productive Time: Allocated days for inclement weather and indoor processing = Non-productive calendar days × [Field calendar days for a specific work method / (Total annual field calendar days － Non-productive calendar days)].

Standardized Quota Calculation: Field quota days for a specific work method = Actual calendar working days + Allocated non-productive days.

Annual Workload Area: Sourced from the aggregated field log records.

Group-day Efficiency Formula: Group-day efficiency = Annual workload / (Field quota days × Number of project teams conducting the work).

The resulting statistical matrix for time utilization in environmental geological mapping (Table 1) enables cross-project and cross-method comparison. This study introduces an innovative dynamic allocation mechanism for non-productive time, effectively mitigating weather-related distortions in efficiency evaluation and supporting refined management and optimal resource allocation.

Table 1 Time Utilization Structure of 1:50,000 Environmental Geological Mapping Field Teams

Province	Working Methods	Field Work Calendar Days	Field Time Utilization Structure	Allocated Days for Adverse Weather and Data Processing	Standard Field Work Days	Workload Area (km^2)	Group Daily Efficiency(km^2/day)
Hebei and Beijing	1:50,000 Environmental Geological mapping	35	17%	11	46	1600	34.8
	Other Field Work	124	59%	39	163		
	Indoor Work Time	50	24%	0	50		
Liaoning	1:50,000 Environmental Geological mapping	35	17%	11	46	800	17.4
	Other Field Work	124	59%	39	163		
	Indoor Work Time	50	24%	0	50		
Heilongjiang	1:50,000 Environmental Geological mapping	54	28%	19	73	350	4.80
	Other Field Work	89	46%	31	102		
	Indoor Work Time	50	26%	0	9		
Neimenggu	1:50,000 Environmental Geological mapping	19	10%	1	20	400	10.0
	Other Field Work	159	85%	8	167		
	Indoor Work Time	9	5%	0	9		
Yunan	1:50,000 Environmental Geological mapping	516	45%	162	678	1400	2.0
	Other Field Work	348	31%	110	458		
	Indoor Work Time	272	24%	0	272		

Jilin	1:50,000 Environmental Geological mapping	35	56%	20	55	800	14.5
	Other Field Work	5	7%	3	8		
	Indoor Work Time	23	37%	0	23		
Hubei	1:50,000 Environmental Geological mapping	80	48%	35	115	550	4.8
	Other Field Work	35	21%	15	50		
	Indoor Work Time	50	31%	0	50		
Fujian	1:50,000 Environmental Geological mapping	108	56%	5	113	920	8.2
	Other Field Work	76	40%	3	79		
	Indoor Work Time	8	4%	0	8		
Zhejiang	1:50,000 Environmental Geological mapping	545	88%	48	593	4400	7.4
	Other Field Work	22	4%	2	24		
	Indoor Work Time	50	8%	0	50		
Anhui	1:50,000 Environmental Geological mapping	40	70%	13	53	400	7.5
	Other Field Work	3	5%	1	4		
	Indoor Work Time	14	25%	0	14		
Shandong	1:50,000 Environmental Geological mapping	23	42%	21	44	175	4.0
	Other Field Work	6	11%	5	11		
	Indoor Work Time	26	47%	0	26		
Henan	1:50,000 Environmental Geological mapping	240	51%	39	279	3800	13.6
	Other Field Work	165	35%	26	192		
	Indoor Work Time	65	14%	0	62		
Guangxi	1:50,000 Environmental Geological mapping	76	50%	20	96	250	2.6
	Other Field Work	44	29%	12	56		
	Indoor Work Time	32	21%	0	32		
Shanxi	1:50,000 Environmental Geological mapping	50	59%	15	65	600	9.2
	Other Field Work	15	18%	5	20		
	Indoor Work Time	20	24%	0	20		
Qinghai	1:50,000 Environmental Geological mapping	110	61%	31	141	680	4.8
	Other Field Work	30	17%	9	39		
	Indoor Work Time	40	22%	0	40		

Xinjiang	1:50,000 Environmental Geological mapping	86	61%	23	109	400	3.7
	Other Field Work	24	17%	7	31		
	Indoor Work Time	30	21%	0	30		

As shown in Table 1, the calculated "Group Daily Efficiency" for 1:50,000 environmental geological mapping exhibits a considerable range (2.0–34.8 km²/day) across provinces. This variation reflects the substantial influence of region-specific operational conditions. The primary factors contributing to this dispersion include:First, Topography and Accessibility: Projects in regions with complex terrain (e.g., Yunnan, Heilongjiang) or poor road access inherently require more time per unit area surveyed, leading to lower efficiency values. Second, Project Phase and Familiarity: Teams in the initial reconnaissance or final detailed verification phases of a project typically cover less area per day compared to those in the main high-productivity surveying phase. Third, Regional Climate and Working Window: Effective daily working hours are compressed in areas with extreme weather, reducing daily output.

Given this expected and justified variation, selecting a single representative value for nationwide budget standards requires a robust statistical approach. We chose the statistical mode (4.8 km²/day) as the standard efficiency value for several reasons. First, it represents the most frequently occurring value in the dataset, indicating it is the most common productivity level achieved under typical field conditions across diverse projects. Second, the mode is less sensitive to extreme outliers (both high and low) than the mean, providing a more stable and central benchmark that is not skewed by exceptionally favorable or challenging one-off conditions. Third, using the mode aligns with the principle of establishing a baseline standard that is achievable for a majority of projects, upon which regional and complexity adjustment coefficients can be applied to tailor budgets to specific contexts. Therefore, 4.8 km²/day serves as a rational, data-driven foundation for the subsequent budget calculation model.

② Personnel Configuration

Personnel allocation is output-based and determined via a position-oriented approach, allowing flexible one-to-one, one-to-many, or many-to-one assignments. We developed a comprehensive framework in line with the "completeness" principle and the Technical Requirements for Environmental Geological Mapping (1:50,000) (DD2019-07) [32], tailored to conditions observed across 16 project teams. Roles are categorized as follows:

Project Management: Includes one Project Manager and one Deputy Manager per project. Data from 16 projects indicate that an average project completes two map sheets annually, each requiring one manager and executed by two field teams.

Field Teams: Adopting the structure specified in the Specification for Geological Survey Field Operations (DZ/T 0251-2022) [33], each standard team comprises one Team Leader (Technical Supervisor), one Technician, one General Administrator (handling safety and logistics, supporting up to two teams), and one Sample Collector.

This configuration minimizes redundancy while ensuring safety and efficiency (Table 2), overcoming the limitations of experience-based decisions and providing a quantitative basis for industry quotas.

Table 2 Personnel Allocation for 1:50,000 Environmental Geological Mapping Field Teams.

No.	Position	Professional Qualifications	Personnel Quota per Team
1	Project leader	Senior Professional Title	0.25
2	Project vice-leader	Associate Senior Professional Title	0.25
3	Map director	Associate Senior Professional Title	0.5
4	Team leader	Intermediate Professional Title	1
5	Team member	Intermediate Professional Title	1
6	Comprehensive management (safety, logistics)	Junior Professional Title	0.25
7	Sample Collector	Skilled Worker	1

Note: Given that the annual workload for one project is 2 map sheets and each map sheet requires 2 survey groups, a total of 4 survey groups are needed per project annually.

③ Material Consumption

Given the diversity and continuity of material usage in environmental geological mapping, establishing consumption quotas is challenging. This study analyzed consumption data from 16 projects, with annual means for each material item summarized in Table 3.

Table 3 Material Consumption for 1:50,000 Environmental Geological Mapping Field Teams.

No.	Material	Annual Consumption per Team	No.	Material	Annual Consumption per Team	No.	Material	Annual Consumption per Team
1	geological hammer	8 set	26	stapler	6 set	51	lockbox	2 set
2	Geological package	8 set	27	magnifier	6 set	52	Fire Extinguisher	2 set
3	compass	8 set	28	Solid glue	12 set	53	Instrument box	20 set
4	sampling bag	300 set	29	light disk	6 set	54	curtain	2 set
5	sampling bottle	200 set	30	storage box	6 set	55	Camera	2 set
6	water sampler	6 set	31	socket	6 set	56	flashlight	6 set
7	Sample storage box	20 set	32	ruler	6 set	57	glove	30 set
8	Self sealing bag	300 set	33	power bank	6 set	58	mouse	6 set
9	Engineer shovel	8 set	34	sensor	6 set	59	mouse pad	6 set
10	wrench	4 set	35	printing paper	6 set	60	casing clamp	20 set
11	Tool knife	8 set	36	filing box	20 set	61	Projector Mounts	1 set
12	scissors	8 set	37	calculator	6 set	62	bracket	6 set
13	marking pen	30 set	38	binder clip	150 set	63	toner cartridge	2 set
14	Gel Pen	30 set	39	rubber	20 set	64	tinfoil	6 set
15	pencil	30 set	40	Wallet	6 set	65	Laptop Bag	6 set
16	pencil case	6 set	41	staple remover	6 set	66	electric kettle	2 set
17	pen container	6 set	42	Document	12 set	67	power supply	1 set
18	Record card	30 set	43	document bag	12 set	68	U disk	2 set
19	Logbook	18 set	44	document box	30 set	69	external hard	6 set
20	adhesive tape	12 set	45	folder	30 set	70	tissue	60 set
21	Pencil sharpener	8 set	46	Box	12 set	71	basket	6 set
22	post-it	6 set	47	Cutting pad	6 set	72	broom	2 set
23	Identification cards	80 set	48	radiator	6 set	73	mop	2 set
24	battery	60 set	49	wire	30 set	74	barrel	6 set
25	staple pin	12 set	50	Roller cutting	1 set	75	First aid kit	6 set

④ Equipment Configuration

Modern survey equipment—such as mapping tablets and unmanned aerial vehicles (UAVs)—has greatly improved field data acquisition and processing efficiency [34]. We implemented a dual-level quota system ("Map Sheet–Field Team") to optimize resource use through shared allocation. For example, each map sheet is allocated two mapping tablets, enabling one tablet per field team. Other equipment allocations are detailed in Table 4.

Table 4 Equipment Configuration for 1:50,000 Environmental Geological Mapping Field Teams.

No.	Equipment	Quantity per Map	Quantity per Team	No.	Equipment	Quantity of per Map	Quantity per Team
1	Mapping handheld device	2	1	13	Shallow soil drilling	2	1

2	Notebook computer	6	3	14	Water quality meter	2	1
3	camera	2	1	15	Water sampler	2	1
4	projector	1	0.5	16	Water level gauge	2	1
5	MFP	1	0.5	17	peristaltic pump	2	1
6	walkie-talkie	6	3	18	Submersible pump	2	1
7	range finder	1	0.5	19	current meter	2	1
8	Beidou terminal	2	1	20	Point Load Gauge	2	1
9	GPS positioning terminal	2	1	21	Groundwater depth sampler	2	1
10	UAV	0.5	0.25	22	Groove drill	2	1
11	generator	1	0.5	23	fridge	1	0.5
12	turbidimeter	2	1	24	RTK	2	1

⑤ Transportation Quota

The transportation quota reflects the vehicle workload per map sheet. Data from 16 teams show an average of 36,492 km traveled per map sheet per standard team (one off-road vehicle). Thus, the quota per team is set at 18,246 km.

(4) Economic Parameter Calculation

① Wages

Compensation standards are based on National Bureau of Statisticsof China (NBSC) official data submitted to national statistical and labor authorities [35]. Remuneration is strictly tiered by position grade:

Technical personnel: Senior (grades 2-4), Associate Senior (5-7), Intermediate (8-10), Junior (11-13).Skilled workers: Senior (grade 2), Intermediate (3), Junior (4-5). Field allowances are excluded from these figures. Details are provided in Table 5.

Table 5 Salary Parameters for 1:50,000 Environmental Geological Mapping Field Teams

Professor (CNY/person*per moth）				Skilled Workers（CNY/person*per moth）		
Senior	Associate Senior	Intermediate	Junior	Senior	Intermediate	Junior
26235.62	17982.59	14492.54	11542.15	13220.09	11928.07	8619.08

② Field Allowance

According to the “Notice on Adjusting Field Work Allowances for Geological Exploration Personnel” (RenSheBuFa [2014] No. 46) [36], field personnel receive a daily allowance. For this survey, classified as reconnaissance, an expert panel recommended a standard of 80 RMB/person-day to reflect operational intensity and technical demands.

③ Commodity Prices

Prices for materials, equipment book values, and fuel costs were calculated using annual price indices from the National Bureau of Statistics of China (NBSC) and guidance from the National Development and Reform Commission (NDRC), calibrated with actual field expenditure data.

(5) Budget Standard Calculation Model

The model, derived from the Geological Exploration Accounting System, classifies expenditures into three categories: direct costs, indirect costs, and management costs [37]. Direct costs encompass labor (calculated based on staffing levels, wage rates, and field allowances over a standard 250-day work year), materials (annual consumption multiplied by market price), equipment maintenance (original equipment value multiplied by an industry-standard maintenance rate of 2.5%), transportation (including vehicle rental, mileage, and fuel expenses), and other direct costs (accounting for 5% of the total labor and material costs). Indirect costs are allocated for project management and supervision, set at 12.5% of the total direct costs [38]. Finally, management costs, which represent administrative overhead, are calculated as 5% of the combined total of direct and indirect costs [38].

The theoretical budget standard (RMB per unit workload) is calculated as:

Theoretical Budget Standard = (Annual Direct Cost per Team + Annual Indirect Cost per Team + Annual Management Cost per Team) / Annual Workload per Team

Results are rounded to the nearest integer. Methodology and parameters are detailed in Table 6.

Table 6 Budget Standard Calculation Model for 1:50,000 Environmental Geological Mapping Field Teams

No.	Costs	Calculation Formula
1	Direct Costs	1.1+1.2+1.3+1.4+1.5
1.1	Direct Labor Costs	salary standards and field allowances×staffing×work year
1.2	Direct Material Costs	∑prevailing market price×annual consumption volume of each material item
1.3	Direct Equipment Maintenance Costs	∑original value of the equipment ×industry-average maintenance rate of 2.5%
1.4	Direct Transportation Costs	∑Number of vehicles× rental unit price×annual working time+annual mileage×oil price
1.5	Other Direct Costs	（1.1+1.2）×5%
2	Indirect Costs	（1.1+1.2+1.3+1.4+1.5）×12.5%
3	Management Costs	（1+2）×5%
4	Theoretical Budget Standard	（1+2+3）/Annual workload of the team

(6) Adjustment Coefficients

① Geological Complexity

Complex geology (e.g., active tectonics, diverse lithology, high fault density) necessitates greater effort, sampling, and testing, increasing costs. Complexity is graded via metrics including: lithology (attitude variability, assemblage complexity, facies changes), structure (fold complexity, fault density, structural overprinting), topography (elevation range, valley density, traverse conditions), outcrop quality (exposure rate, overburden thickness), and geological hazards (type, activity, distribution density). Based on integrated assessment, three grades—simple, moderate, complex—are defined, with adjustment coefficients applied per the Budget Standards for Geological Survey Projects (2021) [39]. The characteristics, corresponding budget coefficients, and resultant adjusted budget standards per unit area are presented in Table 7.

Table 7 Geological Complexity Levels, Corresponding Budget Coefficients, and Adjusted Budget Standards for 1:50,000 Environmental Geological Mapping

Geological Complexity	Characteristic	Budget Coefficient	Budget Standard (CNY/km^2)
Simple (Level I)	The rock strata have a gentle horizontal or inclined orientation, simple strata, good outcrops, flat terrain, and are easy to pass through.	1.0	621
Medium (Level II)	There are significant folds and faults, unstable lithological changes, moderate outcrops, unfavorable geological phenomena but not complex, large terrain undulations, many rivers and shrubs, sometimes requiring detours	1.2	775
Complex (Level III)	There are complex folds and faults, complex lithological changes, diverse types, poor outcrops, complex geological phenomena, and difficult passage	1.5	972

② Regional Adjustment Coefficient

Significant regional variations in labor, material, and transportation costs across China are accommodated using a dynamic adjustment mechanism. Factors include: field construction period (climate, effective working days), labor costs (provincial wage standards), and logistics (road access, fuel prices, remote area premiums). China is divided into 11 cost correction zones (Supplementary Table 1), with coefficients objectively weighted via an entropy weight-TOPSIS model

Discussion

As a cornerstone of geological hazard prevention, ecological conservation, and territorial spatial planning, environmental geological mapping relies on scientifically sound budget standards to ensure efficiency and cross-regional data comparability [40]. However, China' s current budgeting norms for 1:50,000-scale surveys have not been updated in over a decade, resulting in systemic inadequacies such as regional funding imbalances and compromised data quality. This study establishes a revised budgeting framework that integrates geological complexity, market realities, technological advances, and fiscal policies to support high-quality development in geological surveying. The following sections organize the key insights and implications of this research under thematic subheadings, directly addressing the three specific objectives outlined in the Introduction.

(1)Addressing Spatial Heterogeneity in Geological Environments

The first objective of this study was to introduce a novel method for collecting basic field-level quotas. The core challenge this addresses is the significant spatial heterogeneity of geological environments, which renders uniform cost standards ineffective [40]. Our method of mining and processing 12,843 operational log records directly tackles the data gap created by institutional reforms. This bottom-up, data-driven approach provides the granular, empirical basis for quantifying how factors like terrain and tectonics impact costs. For instance, the analysis reveals that field efficiency in southwestern mountainous areas can be over 40% lower than in eastern plains [41], a variation captured in the "Group Daily Efficiency" range shown in Table 1. The establishment of regional adjustment coefficients and a tiered geological complexity classification is a direct outcome of this detailed quota collection. It moves beyond generalized averages, fulfilling Objective 1 by enabling a budget model that is fundamentally rooted in the variable realities of fieldwork across diverse landscapes

(2) Mitigating Market Distortions and Ensuring Survey Quality

The second objective was to establish a dedicated cost estimation model using an activity-based costing framework. The model's design directly confronts the market distortions arising from outdated standards. By decomposing costs into labor, materials, equipment, and transportation modules and applying the "quantity – price – cost" paradigm, the model creates a transparent, scientifically calibrated benchmark. This addresses the "low-bid, low-quality" dilemma, where inadequate budgets force compromises, such as achieving only 72% of required sampling density in some areas [42]. The model's outputs, detailed in Tables 2 – 6, provide a defensible cost floor derived from actual consumption and efficiency data. Thus, the model fulfills Objective 2 by not only estimating costs but by structuring them in a way that promotes fiscal accountability and ensures funding adequacy for mandatory technical specifications, thereby safeguarding survey quality.

(3) Incorporating Technological and Socioeconomic Changes

The integration of technological and socioeconomic changes into the budget framework is a critical test of the model' s relevance (Objectives 2 & 3). The 2009 quota system is obsolete in the face of rising labor costs, inflation, and the adoption of technologies like UAVs and InSAR. Our model explicitly incorporates these elements by quantifying modern equipment needs (Table 4) and using current-year price indices. While UAVs may reduce some unit costs by 40%, they introduce new expenses, with data processing now accounting for over 35% of related costs [43]. The model captures this shifting cost structure, ensuring budgets support, rather than hinder, technological adoption. This demonstrates the model' s capacity to evolve with operational realities, a key aspect of its empirical validity and practical utility.

(4) Alignment with National Fiscal Policy Reforms

The third objective was to empirically validate the model and provide a scientific basis for fiscal budgeting. The model' s strong alignment with national policy reforms, such as the State Council' s mandate for comprehensive expenditure standards by 2025, constitutes a major form of external validation. By offering a systematic, multi-dimensional framework that meets these top-down policy requirements, the study demonstrates its practical applicability and policy relevance. The model provides the methodological rigor needed to transform broad policy goals into actionable, sector-specific budgeting tools, thereby contributing to the interdisciplinary field of geological economics as intended in Objective 3.

(5)Methodological Innovations, Validation, and Limitations

The methodological innovations—particularly the direct extraction of field log data and the dual-cycle validation combining statistical analysis with Delphi expert consultation—underpin the achievement of all three objectives. These methods ensure the model's foundation is robust and its parameters, like the 80 RMB/person-day field allowance, are credible. Field tests across three complexity tiers showed high accuracy, with budget deviations below 3% (2.1%, 1.7%, 2.5%), providing strong empirical validation. However, the model' s current dataset may underrepresent extreme environments like permafrost or karst regions. Future work should expand geographic coverage and explore dynamic adjustment mechanisms, such as CPI linkage, to enhance long-term relevance and automated updates, further strengthening the model' s scientific foundation.

(6)Limitations and Future Research Directions

While the proposed model offers a scalable framework with significant potential for broader application, its current calibration is based on data from 16 projects at the 1:50,000 scale. The potential for applying this model to other common survey scales, such as 1:25,000 or 1:100,000, is grounded in its modular "quantity – price – cost" architecture and the activity-based costing principle. The core methodology—deriving basic quotas (personnel, efficiency, materials) from field logs and adjusting them with complexity and regional coefficients—is theoretically transferable. For instance, a 1:25,000 survey would require adjustments to the basic productivity quota (e.g., a lower km^2/day efficiency due to higher detail density) and potentially the material consumption quotas (e.g., higher sampling density per unit area). Conversely, a 1:100,000 survey might operate with a higher baseline efficiency. The model' s structure can accommodate these changes by scaling the "quantity" inputs while retaining the same cost calculation formulas.

However, specific limitations must be acknowledged for cross-scale application. First, the economic parameters, particularly the division between direct and indirect costs, may not scale linearly. The intensity of management oversight and data processing for a large-area, small-scale map might differ proportionally from that of a detailed, large-scale survey. Second, the equipment configuration profile could shift significantly; larger-scale surveys may rely more on high-resolution remote sensing and detailed geochemical analysis, altering the capital cost structure. Third, the current geological complexity coefficients (Table 7) are calibrated for the 1:50,000 operational context and may require re-validation for other scales, as the impact of a given geological feature on survey cost is scale-dependent.

Therefore, while the framework is portable, successful application to scales like 1:25,000 or 1:100,000 would necessitate scale-specific recalibration of key input parameters. Future research should focus on collecting parallel datasets for these scales to empirically determine the scaling functions for productivity, consumption, and equipment use. Integrating such scale-adaptive mechanisms would transform the model from a scale-specific tool into a universal budgeting system for environmental geological mapping.

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Author contributions statement

Conceptualization and methodology, Gan Luo, Mingqi Tao,; formal analysis, Shuai Zhong and Gan Luo.; investigation, data curation and resources, Gan Luo, Mingqi Tao; writing—original draft preparation, Gan Luo and Shuai Zhong; writing—review and editing, Gan Luo and Shuai Zhong; project administration and funding acquisition, Mingqi Tao,Chunqian Cao,and Gan Luo. All authors have read and agreed to the published version of the manuscript.

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Additional information

Conflicts of Interest: The authors declare no conflict of interest.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.