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System Design and Operational Strategy for Radiopharmaceutical Waste Decay Tanks Using Patient Load Profiling in a Hospital Nuclear Medicine Facility

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Abstract

Background: Radiopharmaceutical liquid waste requires radionuclide-specific retention, whereas decay tanks are often sized based on average wastewater flow.
Objective: To develop a patient-load-based decay tank design and operating strategy for the planned nuclear medicine facility at Bali International Hospital.
Methods: An engineering design approach integrated planned weekly patient loads, administered activities, surveyed water use, and radioactive accumulation and decay modeling. The adopted aqueous discharge criterion was 0.01 MBq/L, derived from the iodine-131 (I-131) clearance level of 10 Bq/g.
Results: The planned service profile comprised 58 diagnostic and 42 therapeutic patients per week, generating 7,750 L and 3,900 L of wastewater, respectively. Following a 10-week filling period, therapeutic effluent was modeled to have an activity concentration of 4.43 MBq/L and required 11 weeks of isolated decay. Diagnostic effluent required approximately 39.6 hours to reach the criterion; a 3-day retention period was therefore adopted. The proposed segregated configuration comprises three 40,000-L therapeutic tanks and three 10,000-L diagnostic tanks. Segregation avoids approximately 85,000 L of additional storage compared with retaining diagnostic effluent for the therapeutic decay period.
Conclusion: Patient-load profiling supports distinct capacity and rotation strategies for diagnostic and therapeutic radioactive waste. Model-predicted compliance with the discharge criterion does not, by itself, authorize discharge without activity measurement, input reconciliation, and regulatory verification.

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INTRODUCTION

Every nuclear medicine procedure, whether diagnostic or therapeutic, generates a common by-product: liquid waste containing radionuclides excreted by patients (Berckmans et al., 2025; Judge et al., 2023; Qaim et al., 2016; Synowiecki et al., 2018). In a facility that provides both diagnostic and therapeutic services, this waste cannot simply be discharged to the hospital wastewater treatment plant without appropriate radioactive-waste controls, because studies have repeatedly found that conventional municipal wastewater treatment does not fully remove radionuclides of medical origin from the water it processes (Sancho et al., 2021). A common control measure is decay in storage, in which liquid radioactive effluent is retained in dedicated

tanks until its activity has decreased to a level that meets the applicable regulatory discharge criteria (International Atomic Energy Agency [IAEA], 2000). Decay in storage is effective because many radionuclides used in nuclear medicine have relatively short half-lives compared with typical hospital operating timescales. The effluent is isolated in a tank, its activity decreases according to the radioactive decay law, and the contents are released only after appropriate measurements confirm compliance with the applicable release criteria (Goddard, 1999; IAEA, 2000). Multi-tank configurations allow one tank to receive effluent while another remains in storage for radioactive decay, supporting continuous service and reducing the risk of overflow associated with single-tank systems. This operating principle is consistent with findings from routine surveillance of operational delay-and-decay facilities (Kaur et al., 2024). Because the planned service mix includes both diagnostic radiopharmaceutical procedures and radionuclide therapies, the infrastructure must accommodate distinct radioactive-effluent loads rather than treating the waste as a uniform hospital wastewater stream. The principal concerns are potential radiation exposure from uncontrolled releases, compliance with authorized discharge conditions, and the limited ability of conventional wastewater treatment processes to reliably remove dissolved radionuclides.

The design of decay-in-storage systems is complicated by the interaction between two governing variables: retention time and effluent volume. The required retention time depends on the radionuclides present, their half-lives, and the applicable discharge criteria; it cannot be reduced simply through changes in tank geometry or operating arrangements. The radionuclides involved also span more than two orders of magnitude in half-life. Technetium-99m (Tc-99m), which is widely used in diagnostic imaging, has a half-life of approximately 6.02 h, meaning that effluent containing this radionuclide can generally reach the applicable release criteria within days, depending on its initial activity and the required clearance level (Mettler & Guiberteau, 2019). Iodine-131 (I-131), used in thyroid ablation and other therapeutic applications, has a half-life of approximately 8.02 d and may be administered at activities of up to 7,400 MBq; consequently, I-131-containing effluent can govern the required retention period in facilities offering radionuclide therapy. Lutetium-177 (Lu-177) and samarium-153 (Sm-153), used in therapies for metastatic castration-resistant prostate cancer and for bone pain palliation, respectively, have half-lives of approximately 6.65 d and 46.3 h. The growing clinical use of Lu-177-labelled radiopharmaceuticals has also introduced additional waste-management challenges because even trace quantities of the longer-lived radionuclide Lu-177m can extend the effective storage requirement beyond that predicted from the parent radionuclide alone (Prevot et al., 2023). When effluent containing both short- and long-lived radionuclides is stored together, the release decision must account for all relevant radionuclides and be governed by whichever constituent or regulatory criterion is most restrictive. Consequently, the Tc-99m fraction may occupy tank capacity throughout a retention period determined by I-131, even though Tc-99m would not require such prolonged storage if managed separately.

Tank volume, by contrast, depends on the quantity of liquid generated during the required retention period. A therapeutic service treating patients with high administered activities may require prolonged retention, allowing a substantial volume of effluent to accumulate. A busy diagnostic service may require only a few days of storage for some radionuclides, permitting more frequent tank turnover. Combining both streams in a single tank system can therefore force short-lived radionuclides to remain in storage for longer than necessary, potentially mixing effluent streams with different activity profiles and consuming storage capacity without providing a corresponding radiological benefit. Consequently, relying on average flow rates can obscure variations in patient attendance, procedure-specific administered activities, and water consumption, potentially resulting in unnecessary storage capacity or insufficient capacity to accommodate peak service demand.

Patient excretion patterns also influence the proportion of administered activity that enters the liquid-waste system, and recent clinical dosimetry studies have provided further insight into these processes. Urinary excretion of I-131 in patients undergoing thyroid treatment has been reported to exceed 75% within 24–36 h and to reach approximately 85% over a five-day inpatient stay (Ravichandran et al., 2011). For Lu-177-labelled radioligand therapies, the proportion of administered activity excreted during the first several hours after administration

can also be substantial. Protocols developed for waste handling in hemodialysis settings report that approximately half of the administered activity may be excreted within about 6 h, predominantly through urine (Kupitz et al., 2025). Facility-level surveillance further indicates that these excretion patterns can translate into measurable changes in tank activity during routine operation. For example, weekly radiation surveys of an operational delay-and-decay tank system serving a high-dose iodine therapy ward tracked exposure rates in relation to tank filling and emptying over a twelve-week monitoring period. The reported measurements remained within the applicable regulatory limits, with no evidence of leakage (Kaur et al., 2024).

Earlier engineering studies of decay tanks have primarily focused on radioactive activity, partly because discharge criteria are commonly expressed in terms of activity concentration or total activity. Zhang & Ge (2024) derived an upper bound for the total I-131 activity that could be accommodated in a full decay tank and presented equations for estimating the minimum decay time and tank volume, validating their approach against monitoring data from four operating hospitals. A subsequent study extended this approach to Lu-177 and reformulated the design problem around environmental discharge constraints rather than occupational dose limits alone (Yunwen, 2025). Surveillance studies have likewise reported that properly operated delay tanks can maintain radioactive discharges well below applicable regulatory limits (Ravichandran et al., 2011). In addition, a field study of the wastewater treatment plant serving a radioiodine therapy unit in West Java, Indonesia, found I-131 activity concentrations in decay tanks and collection channels that were substantially higher than those detected farther downstream. These findings underscore the importance of controlling radioactive effluent at the source rather than relying on municipal wastewater treatment as the primary means of radionuclide removal (Puspita et al., 2023). These studies address complementary but distinct questions: Zhang & Ge (2024) and Yunwen (2025) formulate activity-based and discharge-constrained sizing methods, whereas Puspita et al. (2023) examine operational surveillance and environmental pathways. Collectively, they support the need for radioactive decay control. However, the studies reviewed here do not provide the same integrated assessment of service-specific patient loads, water consumption, and tank rotation that is undertaken in the present design.

Where decay in storage alone cannot reduce radionuclide activity sufficiently within the available storage period, or where space for tank installations is limited, adsorption has been investigated as a means of removing I-131 directly from effluent rather than relying exclusively on radioactive decay. Nuclear wastewater treatment more broadly identifies adsorption and membrane-based processes among the more technologically mature approaches to radionuclide removal from aqueous waste, alongside chemical, biological, physical, and electrochemical alternatives (Al Saadi et al., 2026; Yazdani et al., 2024; Zhuang & Wang, 2024). Complementary research on radioimmunoassay effluent indicates that similar treatment strategies may be useful when waste-management requirements are influenced by considerations beyond radionuclide half-life alone. Ultrafiltration and reverse osmosis have been investigated for treating iodine-125 (I-125)-bearing laboratory waste, potentially allowing discharge under conditions in which the untreated waste would otherwise require prolonged storage because of its low activity and other waste-management considerations (Sancho et al., 2021). A recent scoping review of sustainability initiatives across nuclear medicine services places decay-tank design within the broader effort to reduce the environmental footprint of the specialty. However, the review indicates that liquid-waste management is still addressed primarily through general principles rather than service-specific design methodologies (Ribeiro et al., 2025).

Much of the existing research, both historical and recent, begins with a fixed or averaged waste-generation rate. Patient load, which directly influences both the activity entering the tank and the volume of effluent accumulating within it, is less frequently treated as an explicit design variable. More precisely, the decay-tank sizing and monitoring studies cited here do not explicitly demonstrate the integrated, service-by-service assessment of projected patient numbers, administered activities, measured water use, and tank rotation undertaken in the present study. This represents a gap in the body of literature reviewed rather than evidence that patient-based design methods do not exist elsewhere.

This gap is particularly important at the design stage, before a facility begins operating and before empirical effluent-monitoring data become available. Bali International Hospital is at

this stage: its nuclear medicine unit is planned, the decay-tank system has not yet been constructed, and tank capacity, retention time, and operating sequence must therefore be determined from a projected service mix. Accordingly, this study begins with patient-load profiling. It develops a service-level profile of weekly patient numbers and administered activities for both diagnostic and therapeutic services; estimates effluent volumes using surveyed water-consumption data rather than assumed excreta volumes; establishes an activity balance that accounts for the accumulation of incoming radioactive effluent while radioactive decay occurs; and evaluates whether the calculated retention periods are sufficient to meet the clearance criteria established by the applicable national regulator. The objective is to design and assess a segregated liquid radioactive-waste decay-tank configuration for the planned hospital nuclear medicine facility using patient-load profiles, activity accumulation and radioactive decay, water-use-based volume estimates, clearance criteria, and a practicable tank-rotation schedule. The contribution of this study lies in integrating established engineering calculations and applying them to the hospital's projected service mix, rather than proposing a new theory of radioactive decay. The practical outcome is a transparent basis for capacity planning and operational discharge controls, subject to verification during commissioning and subsequent operational monitoring.

METHOD

The study followed an engineering design research approach, combining quantitative modelling of waste generation and radioactive decay with a qualitative assessment of compliance with regulatory requirements. The system boundary extended from the points at which effluent left the nuclear medicine unit, primarily the ward toilets and hot laboratory, to the point of discharge into the hospital wastewater treatment plant. Solid radioactive waste, gaseous effluent, and the wastewater treatment plant itself were excluded from the system boundary. The design process involved compiling planned patient capacities and service-specific administered activities, estimating wastewater volumes, calculating influent activity based on explicit excretion assumptions, modelling activity accumulation and radioactive decay over time, assessing compliance with the specified regulatory concentration limit, and determining and verifying tank capacities, changeover intervals, and system redundancy.

The profile was developed from the service inventory planned for the facility. For each examination and therapy type, a representative administered activity was obtained from published dosage guidance Mettler & Guiberteau (2019), while the weekly patient number was derived from the maximum service capacity planned by hospital management for that service. The weekly activity load for each service line was then calculated by summing, across service types, the products of representative administered activity and weekly patient number.

Because the facility was not yet operational, the profile represented the planned service mix and peak load rather than observed temporal variability. The weekly patient numbers were based on planned capacity figures and were therefore treated as a worst-case design load. This approach was deliberate: a design based on peak load would remain adequate at lower utilization, whereas a design based on lower utilization might not provide sufficient capacity under peak-load conditions.

Waste volume estimation

The per-patient wastewater volume was derived from a water-use survey of the planned facility rather than from generic estimates of excreta volume, because most of the liquid reaching the tanks was expected to consist of toilet-flushing and wash water rather than urine alone. The volume accumulated in a tank during a filling phase of duration T was estimated as follows:

$$V = Qp \cdot Np \cdot T \quad (1)$$

where Qp is water use per patient, Np the number of patients per unit time and T the filling duration. Inpatient therapy and outpatient diagnostic attendances differ in both water use and length of stay, so Qp was evaluated separately for each service category and then summed.

Activity estimation and decay modelling

The activity entering the tank per unit time was estimated by multiplying the total administered activity by the assumed excreted fraction, f:

$$Ain = Atotal \cdot f \quad (2)$$

A uniform value of f = 0.70 was adopted as a simplifying design scenario for the fraction of administered activity assumed to enter the liquid radioactive-waste system. This value did not represent a measurement of biological excretion for Tc-99m, I-131, Lu-177, or Sm-153. Although reported urinary excretion of I-131 can exceed this fraction Ravichandran et al. (2011), using 0.70 rather than a higher fraction would reduce the calculated initial activity. Accordingly, this assumption was not conservative with respect to the activity inventory. The actual excretion fractions therefore needed to be verified for each radionuclide and clinical procedure before the design could be accepted.

$$k = (1/2)^{(t / T½)} \quad (3)$$

A tank that remained in the filling phase continued to receive new radioactive activity while its existing contents underwent radioactive decay. Consequently, treating the waste generated over an entire week as a single isolated batch would underestimate the activity inventory. The activity balance was therefore modelled recursively as follows:

$$An = An{-}1 \cdot k + Ain \quad (4)$$

evaluated weekly on the therapeutic line and daily on the diagnostic line. Once a tank is isolated, Ain goes to zero and equation (4) collapses to plain decay. The quantity compared against the regulatory criterion is the activity concentration, A seven-day step represents the weekly planned therapeutic throughput and long I-131 half-life; a 24-hour step represents the five-day diagnostic attendance schedule and comparatively rapid Tc-99m decay. These discrete steps are operating-model approximations, not representations of individual excretion-time profiles. Intermediate discharge times are assessed through the continuous exponential-decay relation after tank isolation.

$$Cn = An / Vn \quad (5)$$

Discharge criterion and evaluation

Annex I of BAPETEN Regulation No. 16/2012 on Clearance Levels specified a value of 10 Bq/g for I-131 (Badan Pengawas Tenaga Nuklir [BAPETEN], 2012). Assuming an aqueous effluent density of approximately 1 kg/L, this value corresponded to an activity concentration of 1×10^4 Bq/L, or 0.01 MBq/L. This value was adopted as the release criterion for both service lines. It was more restrictive than the operational release level of 22.2 MBq/m^3 reported for I-131 effluent in comparable facilities (Ravichandran et al., 2011). The minimum storage time was defined as the earliest time at which the calculated activity concentration fell below the adopted criterion.

The design was evaluated against four criteria. Regulatory compliance required the calculated activity concentration at discharge to fall below the adopted release criterion. Capacity adequacy required the accumulated wastewater volume to remain within the installed tank capacity throughout the filling phase. Rotation closure required the time available to each tank before its next filling cycle to exceed the required storage time. Operational reserve required the configuration to remain functional if one tank became unavailable.

RESULTS AND DISCUSSION

Results

Patient load profile

Table 1 presents the planned patient load and administered activity profile. The two service lines are comparable in terms of patient numbers but differ substantially in their radiological characteristics. The diagnostic line serves more patients and has a lower total weekly administered activity, primarily involving a radionuclide that decays within hours. In contrast, the therapeutic line serves fewer patients but has more than twice the total weekly administered activity, involving radionuclides with half-lives measured in days.

Table 1
Weekly Patient Load And Administered Activity Profile.

Line	Nuclide	Procedure	Activity (MBq)	Patients/week	Weekly activity (MBq)
Diagnostic	Tc-99m	Brain	740	2	1,480
	Tc-99m	Thyroid	185	12	2,220
	Tc-99m	Cardiology	1,665	12	19,980
	Tc-99m	Gastro-hepatobiliary	925	2	1,850
	Tc-99m	Nephro-urology	185	10	1,850
	Tc-99m	Bone	1,110	16	17,760
	Tc-99m	Others	1,110	4	4,440
Subtotal				58	49,580
Therapeutic	I-131	Whole-body scan	370	12	4,440
	I-131	Low-dose therapy	370	12	4,440
	I-131	High-dose therapy	5,550	10	55,500
	Lu-177	mCRPC therapy	9,250	4	37,000
	Sm-153	Bone pain palliation	2,775	4	11,100
Subtotal				42	112,480

Although I-131 whole-body scanning is a diagnostic procedure, it was assigned to the therapeutic line. This segregation strategy was based on radionuclide half-life rather than clinical purpose. Assigning I-131-containing effluent to the diagnostic line would extend the required retention period for that line to accommodate the longer-lived radionuclide, thereby diminishing the operational benefit of separating the two streams.

For the decay calculations, the entire therapeutic activity load was modelled as I-131. Among the three therapeutic radionuclides considered, I-131 has the longest physical half-life. This simplification was intended to provide a conservative estimate of the required storage time by applying the longest half-life to the combined activity inventory. However, the conservatism of this approach depends on the assumed initial activity and the applicable release criterion, and it does not eliminate the need to account for radionuclide-specific discharge requirements.

Waste volume and tank capacity

Table 2 presents the water-use survey results and the corresponding estimated weekly wastewater volumes. An inpatient receiving therapy was assumed to use 90 L of water per day, more than half of which was attributed to bathing, whereas an outpatient diagnostic attendance was assigned a lower water-use allowance. The underlying survey values and patient counts were used to estimate the weekly volumes for each service category.

Table 2
Per-Patient Water Use and the Resulting Weekly Waste Volume.

Category	L/patient/day	Days	Patients/week	Volume (L/week)
I-131 high-dose therapy	90	3	10	2,700
Sm-153 therapy	90	1	4	360
Lu-177 therapy	90	1	4	360
I-131 low-dose and scanning	20	0.5	24	480
Therapeutic total			42	3,900
Diagnostic attendances	75	1	100	7,500
Hot laboratory decontamination	50	5	-	250
Diagnostic total				7,750

Applying Equation (1) to the therapeutic line over a ten-week filling phase yielded a total wastewater volume of 39,000 L (3,900 L/week × 10 weeks). Accordingly, a nominal tank capacity of 40,000 L was selected, providing 1,000 L of additional capacity above the modelled filling

volume. The diagnostic line was modelled over a five-day working week, producing an estimated weekly wastewater volume of 7,750 L. A nominal tank capacity of 10,000 L was therefore selected, providing 2,250 L of additional capacity, equivalent to approximately 29% of the estimated weekly wastewater volume. The larger relative margin in the diagnostic line was intended to accommodate variations in attendance and wastewater generation, although the adequacy of this margin depends on the actual peak daily flow and the operational freeboard required.

Therapeutic stream line

With a total administered activity of 112,480 MBq/week and an assumed excreted fraction of 0.70, Equation (2) yielded an estimated activity input of 78,736 MBq/week. Using a seven-day time step and an I-131 half-life of approximately eight days, Equation (3) yielded a weekly decay factor of 0.5453. Table 3 presents the resulting activity balance during filling and subsequent storage.

Table 3

Activity Balance for the Therapeutic Tank at Selected Steps.

Phase	Week	Activity (MBq)	Volume (L)	MBq/L	Status
Filling	1	78,736	3,900	20.19	filling
Filling	7	170,662	27,300	6.25	filling
Filling	10	172,741	39,000	4.43	isolated
Decay	1	94,187	39,000	2.42	retained
Decay	7	2,475	39,000	0.064	retained
Decay	9	736	39,000	0.019	retained
Decay	10	401	39,000	0.0103	retained
Decay	11	219	39,000	0.0056	below limit

Two features of the filling phase are particularly important. First, the activity inventory approaches a steady state of approximately 172,700 MBq as the activity lost through radioactive decay approaches the activity entering the tank each week. Consequently, extending the filling phase increases the accumulated wastewater volume while producing relatively little additional activity accumulation. Second, the calculated activity concentration decreases throughout filling, from 20.19 MBq/L in the first week to 4.43 MBq/L in the tenth week, because the wastewater volume increases while the activity inventory approaches a steady state. This reduction in activity concentration reflects the combined effects of radioactive decay and increasing liquid volume during filling.

After isolation, the calculated activity concentration falls below the adopted release criterion between the tenth and eleventh weeks of storage, decreasing from 0.0103 MBq/L to 0.0056 MBq/L. The minimum modelled storage time was therefore eleven weeks. Combined with the ten-week filling phase, this resulted in a nominal 21-week filling-and-storage period for each tank. This result superseded the eight-to-ten-week estimate reported in the earlier version of this work, which was based on a single-batch decay model and had not been evaluated against an explicitly stated release criterion. The eleven-week result represents the threshold-crossing time predicted by the stated weekly model; it does not establish that discharge is permissible without verification through appropriate measurements. Because the required filling and storage periods together total 21 weeks, a tank cannot begin another filling phase until its contents have met the applicable release criteria and the operating schedule permits its return to service.

Diagnostic stream line

The planned weekly Tc-99m activity load of 49,580 MBq, multiplied by the assumed excreted fraction of 0.70, yielded an estimated activity input of 34,706 MBq/week. Assuming that this input was distributed uniformly across five working days, the daily activity input was approximately 6,941 MBq. Using a 24-hour time step and a Tc-99m half-life of 6.02 hours, Equation (3) yielded a daily decay factor of approximately 0.0631. Table 4 presents the corresponding activity balance.

Table 4
Activity Balance for the Diagnostic Tank.

Phase	Time	Activity (MBq)	Volume (L)	MBq/L	Status
Filling	Day 1	6,941	1,550	4.48	filling
Filling	Day 3	7,407	4,650	1.59	filling
Filling	Day 5	7,409	7,750	0.956	isolated
Decay	+12 h	1,861	7,750	0.240	retained
Decay	+24 h	467	7,750	0.060	retained
Decay	+36 h	117	7,750	0.015	retained
Decay	+42 h	59	7,750	0.0076	below limit

By the third day of filling, the modelled activity inventory approached a steady state of approximately 7,409 MBq, at which the activity removed through radioactive decay approximately balanced the incoming activity. Accordingly, extending the filling phase would primarily increase the wastewater volume rather than substantially increase the activity inventory. This behaviour explains why the diagnostic line can be strongly influenced by wastewater volume when determining tank capacity, whereas the therapeutic line requires a longer storage period because of the longer-lived radionuclide governing its decay requirements.

The calculated time required for the diagnostic effluent to reach the adopted activity concentration criterion was approximately 39.6 hours after tank isolation. A three-day retention period was therefore adopted as the nominal operating interval, providing additional time beyond the calculated threshold-crossing point and allowing the release process to be coordinated with the weekly operating cycle. Nevertheless, the final release decision must be based on verified measurements and the applicable regulatory requirements rather than the modelled decay time alone.

System configuration and operational strategy

The proposed design comprised six tanks arranged in two independent service lines, with three tanks assigned to the diagnostic line and three to the therapeutic line. The intended operating arrangement provided separate functions for effluent filling, radioactive decay and verification, and the availability of receiving capacity during tank changeover. Table 5 summarizes the design parameters for both lines, and Figure 1 illustrates the proposed configuration. Three tanks per line were specified to allow incoming effluent, isolated contents, and available receiving capacity to be managed separately during normal operation and changeover.

On the therapeutic line, a nominal ten-week filling interval was assigned to each tank. Under a staggered three-tank rotation, successive filling phases would begin approximately ten weeks apart, giving a nominal 30-week interval between successive filling starts for the same tank. This interval exceeds the modelled 21-week filling-and-storage period, providing time for verification and operational changeover. However, this conclusion assumes reliable tank switching, effective valve isolation, sufficient receiving capacity, and confirmation that the stored effluent meets the applicable release criteria before discharge. The third tank therefore serves as an active component of the regular rotation rather than as permanently unused emergency storage.

Table 5
Design Summary of the Two Decay Tank Lines.

Parameter	Diagnostic line	Therapeutic line
Governing radionuclide	Tc-99m (6.02 h)	I-131 (8.02 d)
Patients per week	58	42
Activity input	34,706 MBq/week	78,736 MBq/week
Waste volume	7,750 L/week	3,900 L/week
Filling phase	5 days	10 weeks
Minimum storage time	3 days (39.6 h)	11 weeks
Concentration at discharge	0.0076 MBq/L	0.0056 MBq/L
Number of tanks	3	3

Capacity per tank	10,000 L	40,000 L
Operating cycle per tank	2 weeks	21 weeks

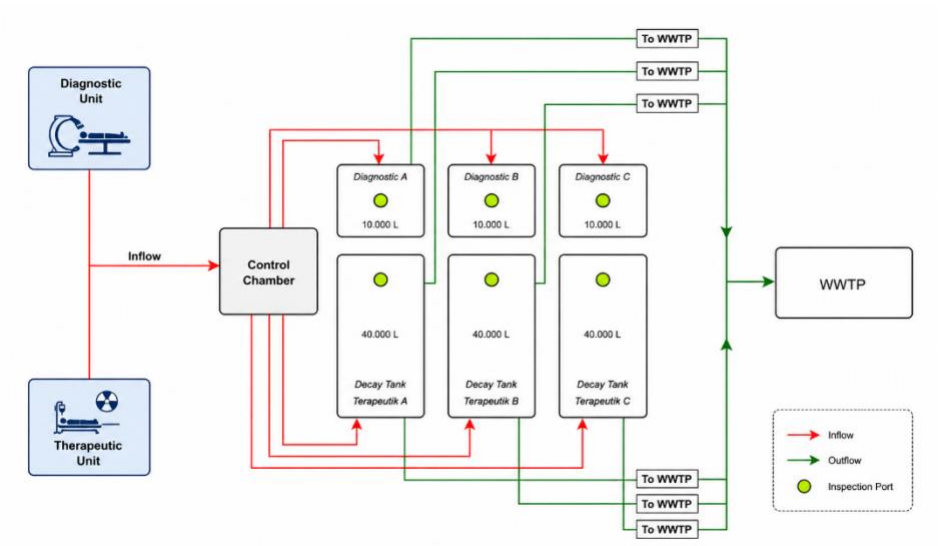


Figure 1. Segregated six-tank decay system with independent diagnostic and therapeutic lines.

Tank changeovers were scheduled according to elapsed operating time and were subject to activity measurements before discharge rather than being triggered solely by tank fill level. Under the modelled load, the therapeutic line required ten weeks of filling followed by approximately eleven weeks of isolated storage for each tank. A staggered three-tank rotation with ten-week filling intervals provided a nominal 30-week interval between successive filling starts for the same tank. During a surge in patient load, the remaining freeboard and projected activity and volume accumulation would need to be reassessed before additional effluent could be accepted. If sufficient capacity or compliance with the required storage period could not be maintained, the facility would need to restrict incoming waste or provide an alternative compliant storage arrangement rather than discharge the effluent prematurely. A tank failure would reduce system redundancy and require the remaining rotation schedule to be reassessed before normal operation resumed. Similarly, the three 10,000-L diagnostic tanks were intended to support separate filling, decay-and-verification, and receiving functions, allowing maintenance without assuming that the calculated 39.6-hour decay period automatically authorized discharge.

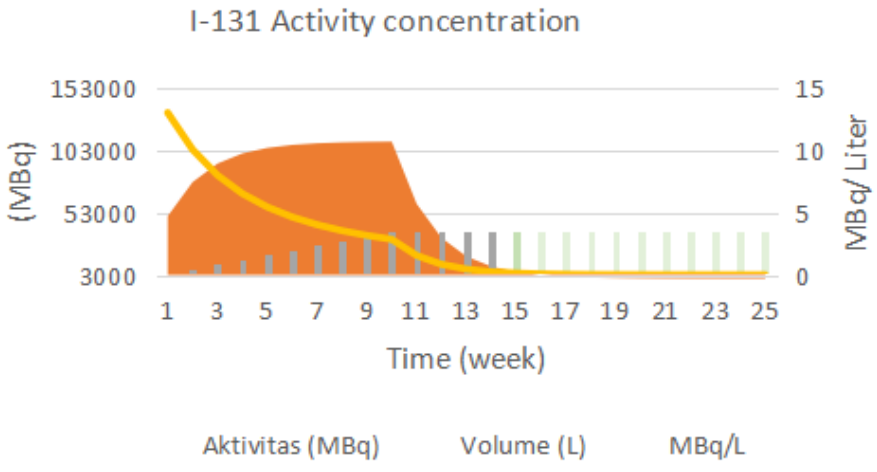


Figure 2. Activity concentration against time on Terapeutic, relative to the clearance level.

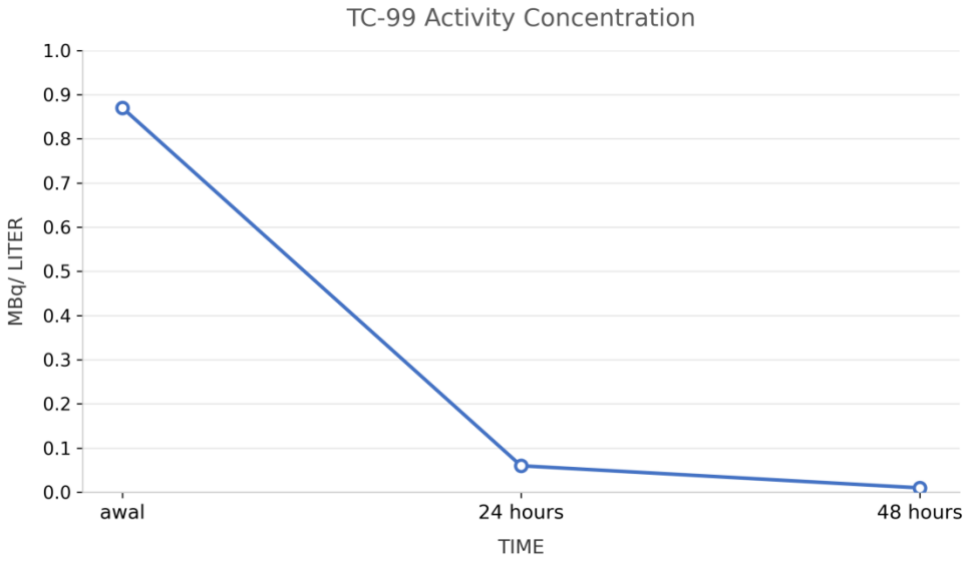


Figure 3. Activity concentration against time on Diagnotic, relative to the clearance level.

Discussion

The benefit of segregating the two service lines can be quantified in terms of storage requirements. If both streams were managed using a common retention period governed by I-131, the diagnostic effluent would also need to remain in storage for approximately eleven weeks under the adopted model. At a wastewater generation rate of 7,750 L/week, this would correspond to approximately 85,250 L of diagnostic wastewater alone during that period. This additional storage requirement would be substantial relative to the proposed tank capacities, without providing a corresponding radiological benefit for the short-lived Tc-99m component. Segregation therefore allows the diagnostic line to operate on a much shorter retention schedule, subject to verification of the applicable release criteria.

Patient-load profiling also clarifies which design constraint governs each service line. The therapeutic line is strongly influenced by radioactive decay and the required storage period, while its tank capacity is determined by the wastewater volume accumulated during the selected filling interval. The diagnostic line, by contrast, has a substantially shorter modelled retention time because Tc-99m decays rapidly, while its required tank capacity is primarily influenced by the volume of wastewater generated during the filling phase. Recognizing these differences allows each line to be sized according to its governing constraints. Such distinctions may be obscured when tank design relies on a single averaged wastewater-generation rate.

The calculated discharge concentrations of 0.0056 MBq/L for the therapeutic line and 0.0076 MBq/L for the diagnostic line were below the adopted criterion of 0.01 MBq/L. Both were also below the operational release level of 22.2 MBq/m^3 reported for I-131 effluent in comparable facilities (Ravichandran et al., 2011). These comparisons do not, by themselves, establish regulatory compliance, because the applicability and measurement basis of the respective criteria must first be confirmed. The calculations also do not rely on dilution in the hospital wastewater treatment plant to achieve the specified activity concentrations.

The findings from the West Java wastewater study provide relevant environmental context because I-131 concentrations were reported to decrease downstream from the decay tanks as the effluent entered and mixed with other wastewater streams (Puspita et al., 2023). Nevertheless, downstream dilution should not be treated as a substitute for adequate radioactive-waste control at the source. The proposed system also provides a basis for reassessing capacity if demand increases, including potential growth in Lu-177-based therapies (Prevot et al., 2023). Final verification remains essential. Each tank was intended to include a suitable inspection or sampling point, with measurements performed using appropriate radiation-monitoring equipment and methods before discharge. The calculated retention periods therefore serve as operational planning estimates rather than substitutes for confirming the actual activity of the stored effluent, consistent with the surveillance practices reported for comparable delay-and-decay facilities (Kaur et al., 2024).

If future increases in patient load cannot be accommodated through additional tank capacity alone, adsorption and membrane-based treatment methods may provide complementary options for reducing radionuclide concentrations in effluent. These approaches have been reviewed by Kadadou et al. (2023), investigated for I-131, and studied for radioimmunoassay effluent by Sancho(Sancho et al., 2021). Such treatment options were excluded from the present system boundary, but they may become relevant if decay in storage increasingly competes with other hospital functions for available floor space. This consideration is consistent with broader discussions of sustainability in nuclear medicine services (Ribeiro et al., 2025).

Limitations

Three limitations qualify these findings. First, the patient-load profile was based on planned service capacity and the projected service mix rather than observed operational variability. Daily and seasonal fluctuations therefore could not be characterized before the facility began operating. Second, an excreted fraction of 0.70 was applied uniformly across both service lines and all radionuclides, despite differences in excretion kinetics among radionuclides and patients (Kupitz et al., 2025). Third, treating the entire therapeutic activity load as I-131 simplified the activity balance but did not represent the individual decay characteristics of Lu-177 and Sm-153. A radionuclide-specific model could produce different storage-time estimates for the individual components. Operational effluent monitoring and verification of patient-load data after commissioning will be needed to evaluate these assumptions and determine whether the proposed design margins are sufficient.

CONCLUSION

This study demonstrated how planned patient loads, administered radionuclide activities, surveyed water consumption, and activity accumulation-and-decay modelling could be integrated to provide a service-specific basis for designing a liquid radioactive-waste storage system for Bali International Hospital. Under the stated assumptions, the planned diagnostic and therapeutic services generated estimated wastewater volumes of 7,750 L/week and 3,900 L/week, respectively, but required substantially different storage periods. The therapeutic stream reached an activity concentration of 4.43 MBq/L after ten weeks of filling and fell below the adopted criterion of 0.01 MBq/L after eleven weeks of isolated storage. The diagnostic stream reached the same criterion after approximately 39.6 hours of decay following isolation. Accordingly, the proposed configuration comprised three 40,000-L therapeutic tanks and three 10,000-L diagnostic tanks, with staggered operation and verification before discharge. Separating the two streams avoided the need to retain the diagnostic wastewater for the longer therapeutic storage period, corresponding to approximately 85,250 L of diagnostic wastewater over eleven weeks at the assumed generation rate.

These findings provide a transparent basis for capacity planning and operating schedules but remain conditional on the projected service volumes, water-use assumptions, uniform excreted fraction of 0.70, and simplified treatment of the therapeutic radionuclides. Before commissioning, the hospital should reconcile inconsistencies in the planned patient throughput and water-consumption data, verify radionuclide-specific excretion and activity inputs, confirm the applicable regulatory discharge criteria, and validate the tank-rotation schedule under variable demand and equipment interruptions. Actual effluent activity must be measured, and all applicable regulatory discharge requirements must be satisfied before any release; modelled retention times alone are insufficient. Future evaluation using operational patient and effluent-monitoring data would improve the reliability of the design and support adjustments to tank capacity and operating procedures.

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AUTHOR CONTRIBUTION STATEMENT

Yosef Derry Sanders Tarigan: conceptualisation, system design, methodology, data analysis, visualisation and manuscript preparation. Tota Pirdo Kasih: supervision, technical evaluation, methodology review and manuscript revision.

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