Tritium Leakage Traces the Path of Cesium from Fukushima Daiichi Nuclear Power Plant into the Ocean

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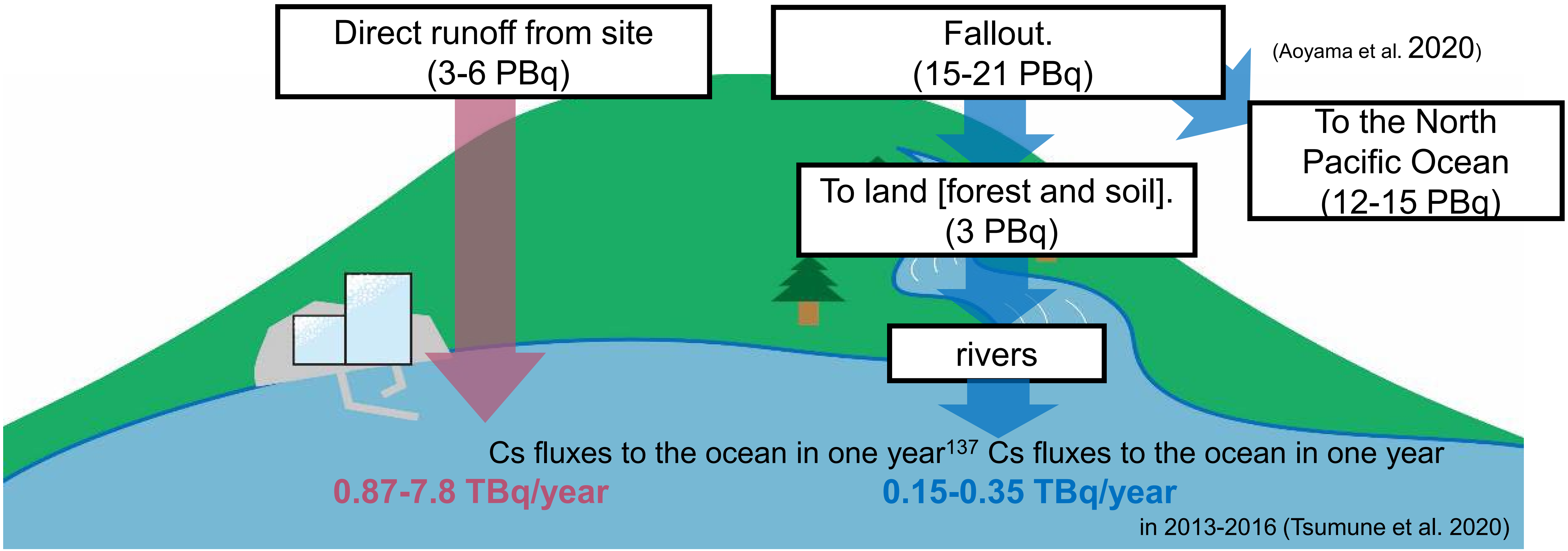
The Pacific Ocean seen from Fukushima Dai

Direct discharge of ^{137} Cs from the site to the sea after the Fukushima Daiichi Nuclear Power Plant accident

Dispersion of radioactive materials due to the Fukushima Daiichi Nuclear Power Plant accident (^{137} Cs)

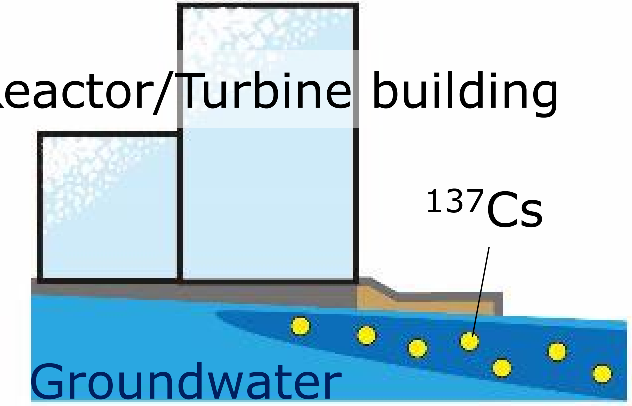


The amount of ^{137} Cs direct leakage from the Fukushima Daiichi Nuclear Power Plant is high.

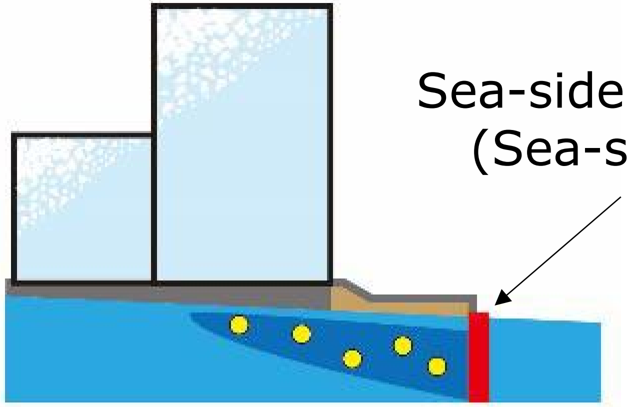
(Background) Cs concentration reduced by sea-side barrier wall137 and still continuing137 Cs leakage

- Installation of sea-side barrier wall… construction completed in October 2015

~October 2015



October 2015-.



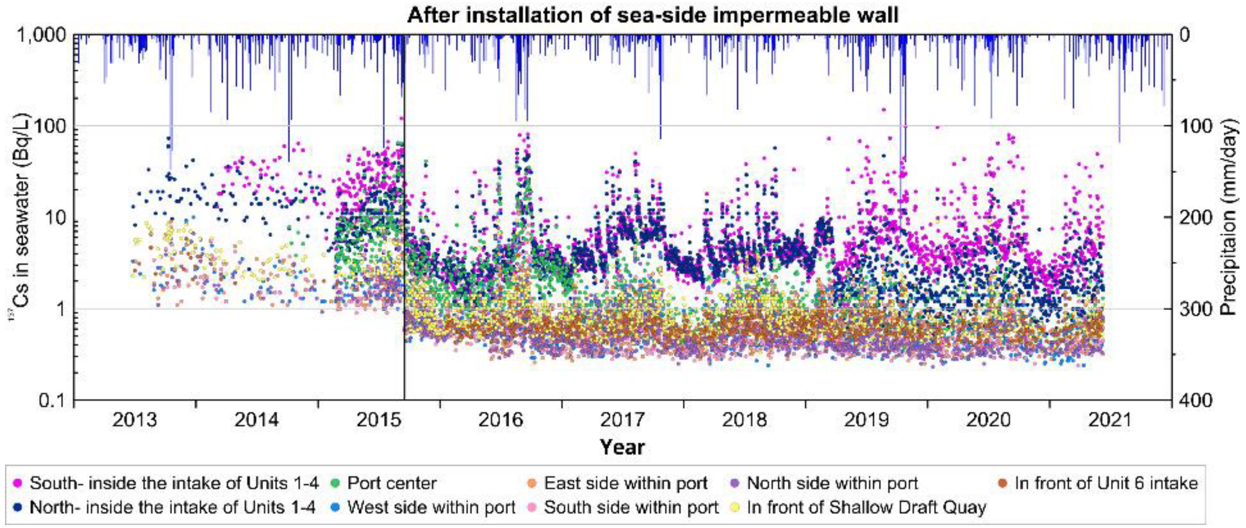


Fig. Concentration of137 Cs in seawater in the port from 2013 to 2021

From August to October,^{137}Cs concentrations increase. (Aoyama et al. 2020, Machida et al. 2020)

^{137}Cs concentrations decreased and seasonal variations were observed.

Has emission by surface currents become dominant?

It is not well understood why this seasonal variation is occurring.

(Background) K drainage channel releasing ^{137} Cs into the harbor

March 2016: total monthly rainfall 22 mm

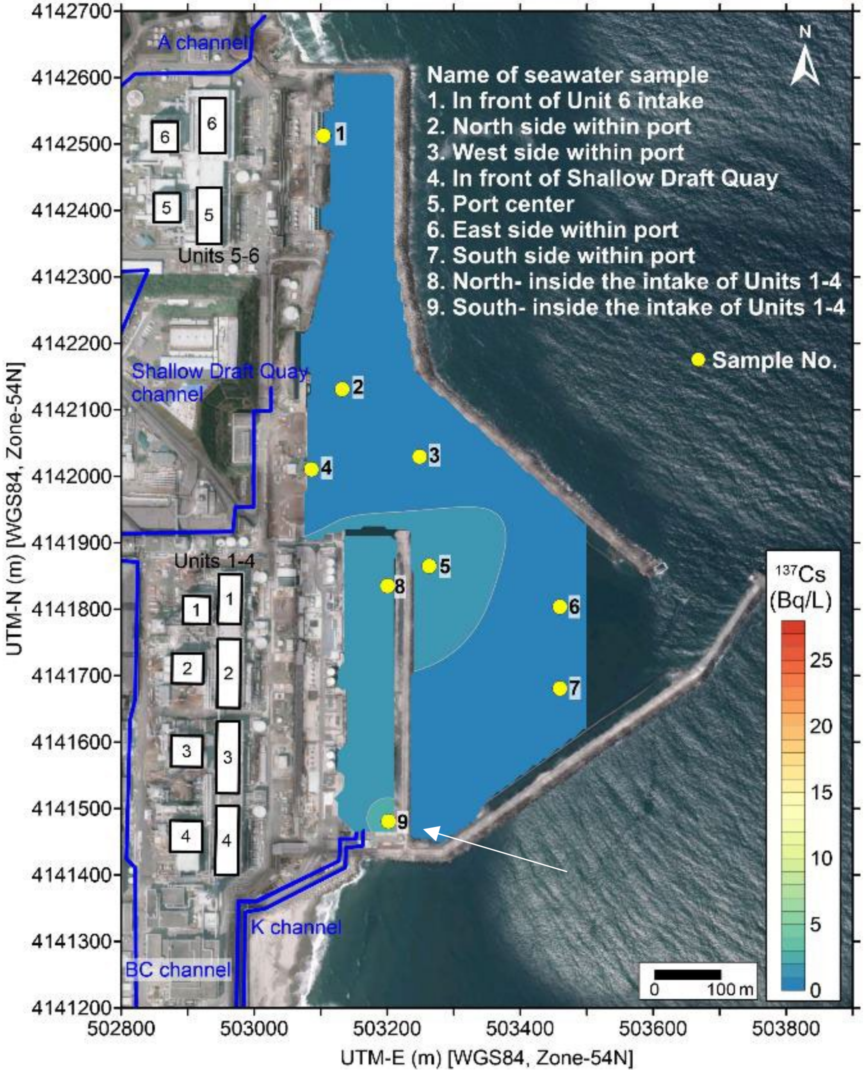


Fig. Distribution of ^{137} Cs concentrations in the inland seawater of the port in March 2016

September 2016: total monthly rainfall 310 mm

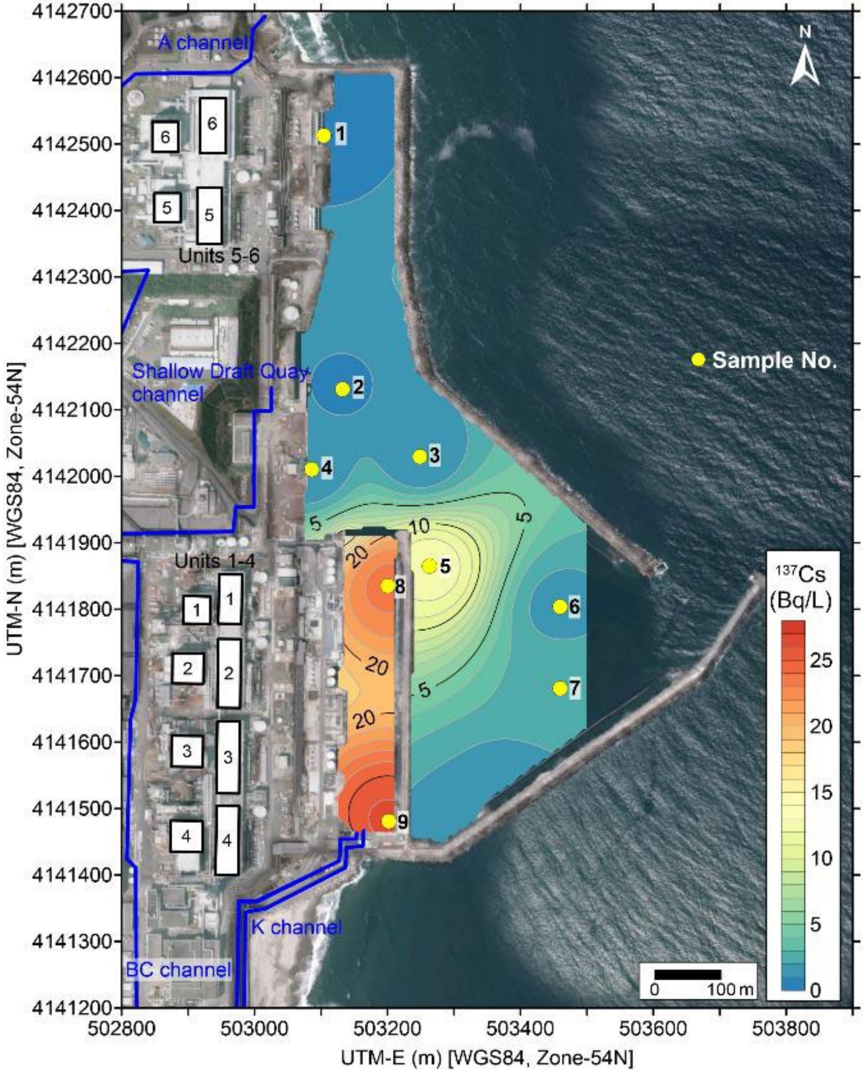


Fig. Distribution of ^{137} Cs concentrations in seawater in the harbor in September 2016

^{137} Cs concentration in seawater is downloaded from TEPCO's HP published data "Analysis Results of Surrounding Area -> Seawater".

Background is GSI aerial photo taken in 2018. Same as below

(Purpose) Can we use ^{3}H from the tank area as a tracer?

- Tritium contamination from contaminated water storage tanks in 2013 and 2014 after the nuclear accident (TEPCO, 2013; 2014) Both surface and groundwater flow out to drainage channel K

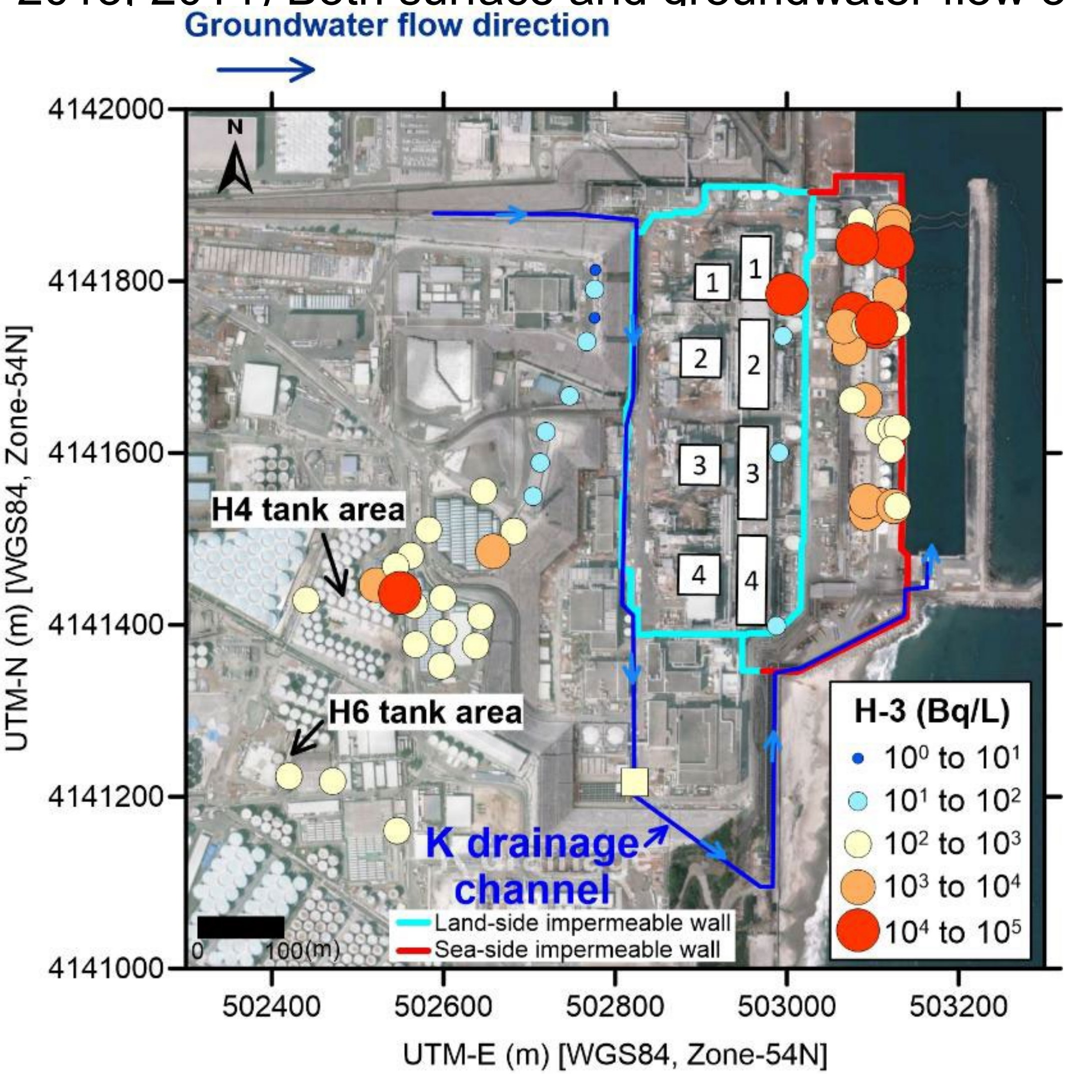


Fig. 2016 average tritium concentrations in groundwater (●) and in drainage channel K (■).

Both surface and groundwater flows into drainage channel K

(surface flow) rainfall origin, and tritium in rainfall is low (0.33 Bq/L, 2016: example from Fukushima City Gusyev et al., 2019).

(Groundwater flow) High concentrations (100-1000 Bq/L) of tritium have been detected in the groundwater.

Tritium concentration in groundwater as end member, Possible mixed model of surface and groundwater flow?

Purpose: Utilize ^{3}H concentrations in groundwater entering drainage canals,
K drainage^{137} to determine the factors contributing to seasonal variations in Cs concentrations.

Where does the water coming into drainage channel K come from?

- K drainage basin (approx. 202,160 m^2)

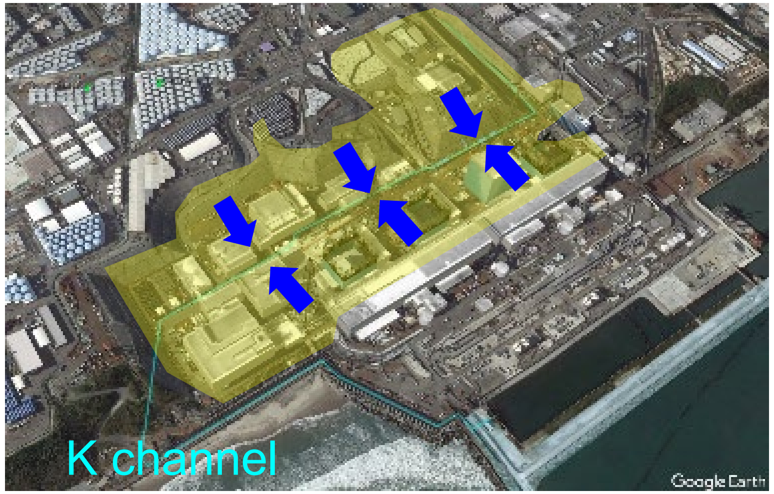


Fig. K drainage basin (yellow colored area)

✓ Surface flow and groundwater from the western plateau and building area is collected in open channels, branch pipes and discharged to the sea.

Fig. Example of a faceted slope and water pathway for runoff into a culvert

✓ Surface facings have been placed around all areas except around the buildings.

✓ Flow increases during rainfall and over long periods.

Sunny days = groundwater only

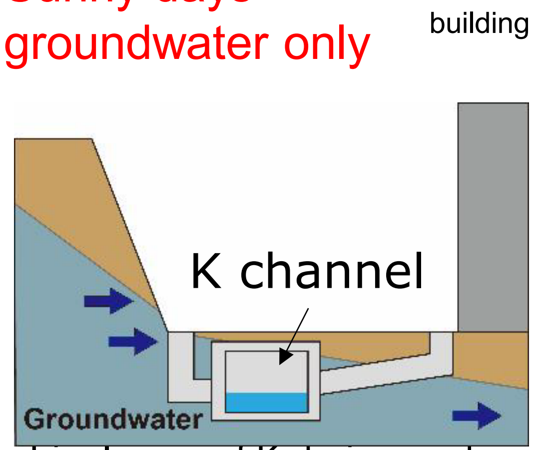


Fig. Image of K drainage channel in clear weather

Rainy weather = surface flow and groundwater

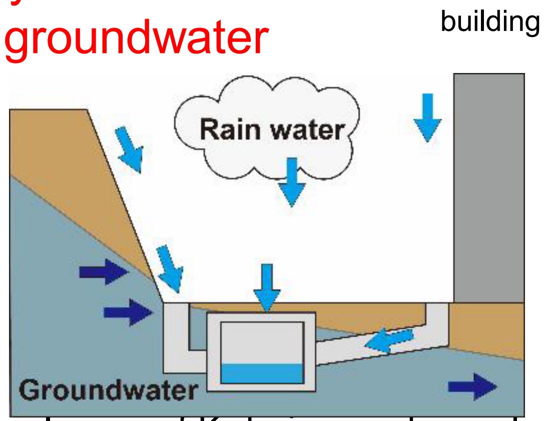


Fig. Image of K drainage channel during rainy weather

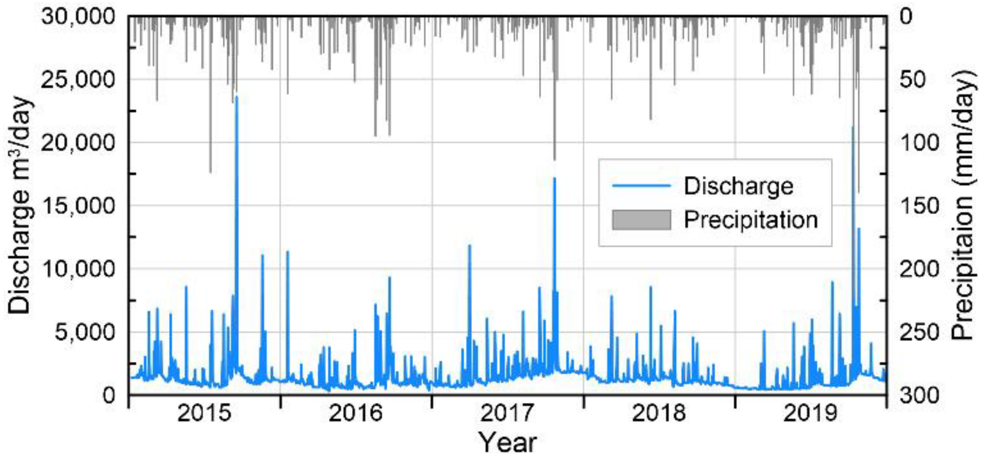


Fig. K drainage channel flows in 2015-2016

Relationship between ^{137}Cs concentration in drainage channel K and ^{137}Cs concentration in seawater in the harbor

- ^{137}Cs concentration in drainage channel K and ^{137}Cs concentration in seawater

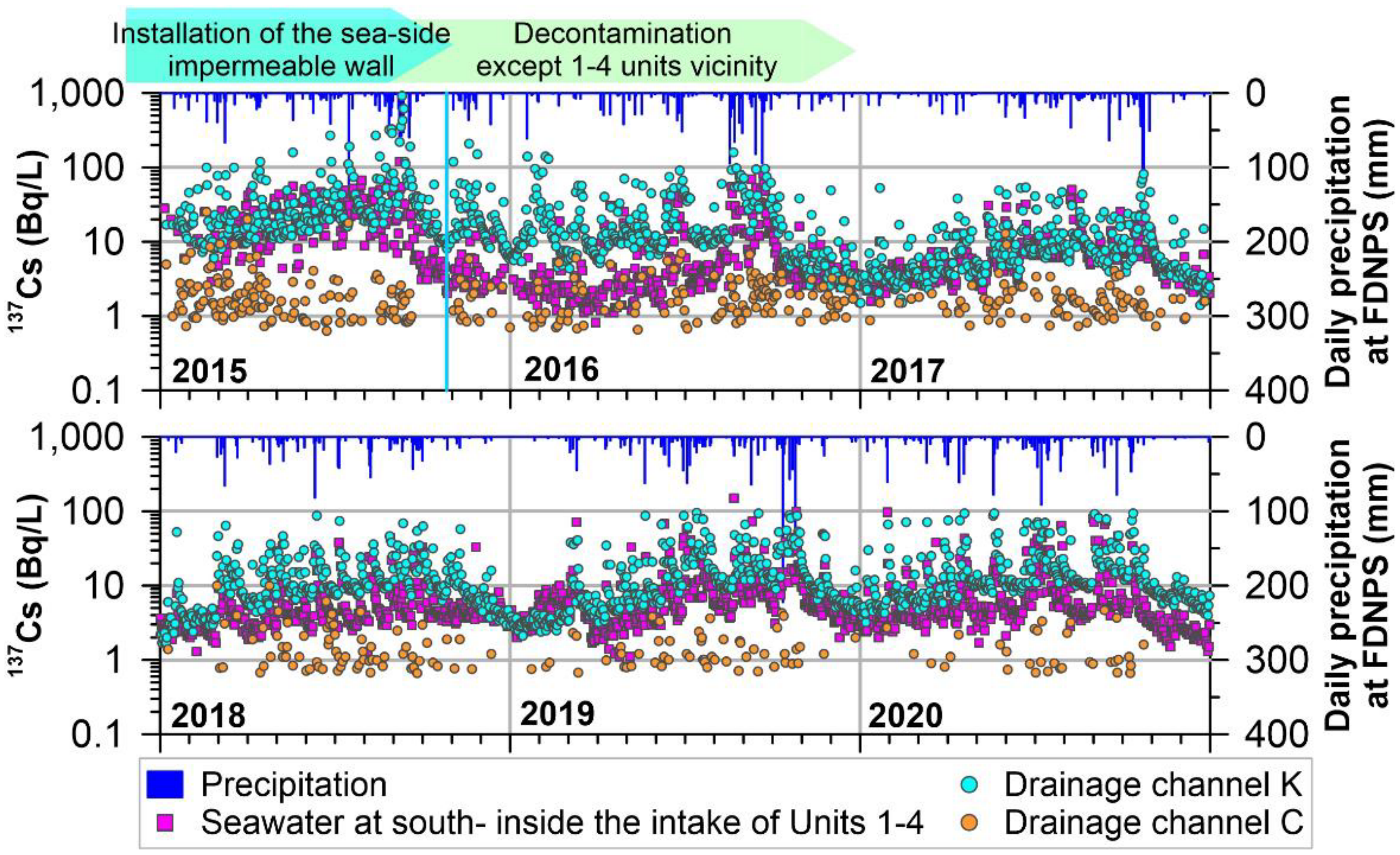


Fig. Relationship between K and C drainage channels and ^{137}Cs concentrations in southern seawater (AGU, 2022)

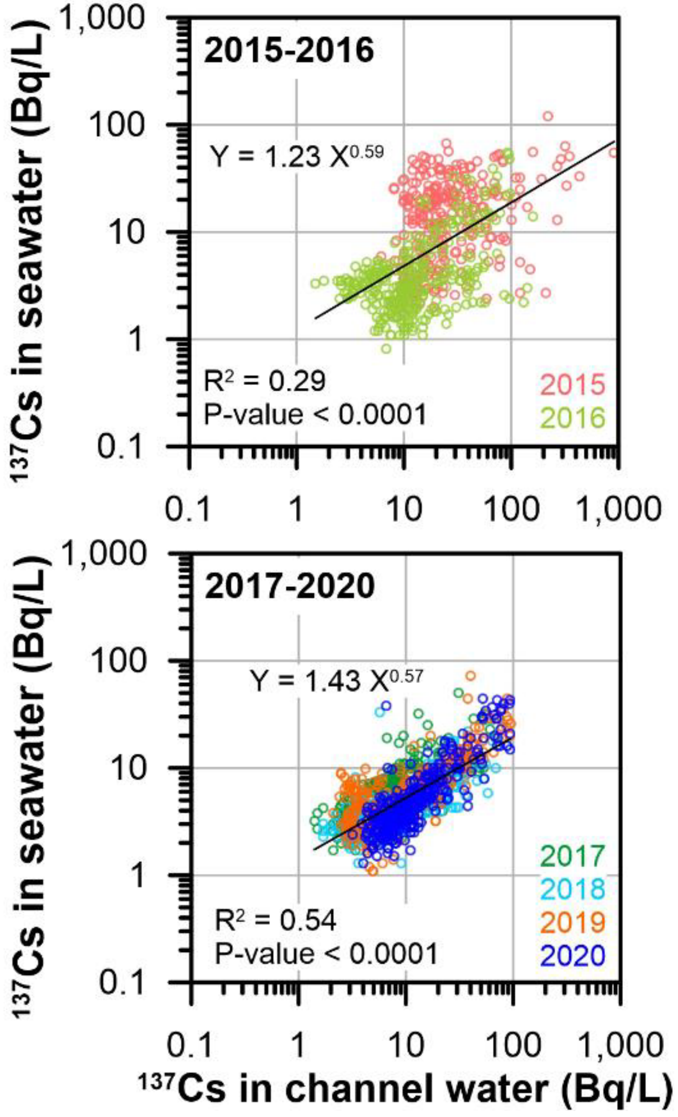


Fig. Correlation between K drainage channel and ^{137}Cs concentrations in southern seawater

Concentration fluctuations in drainage channel K have seasonal variations similar to those of ^{137}Cs concentrations in seawater.

Tritium concentration in drainage channel K

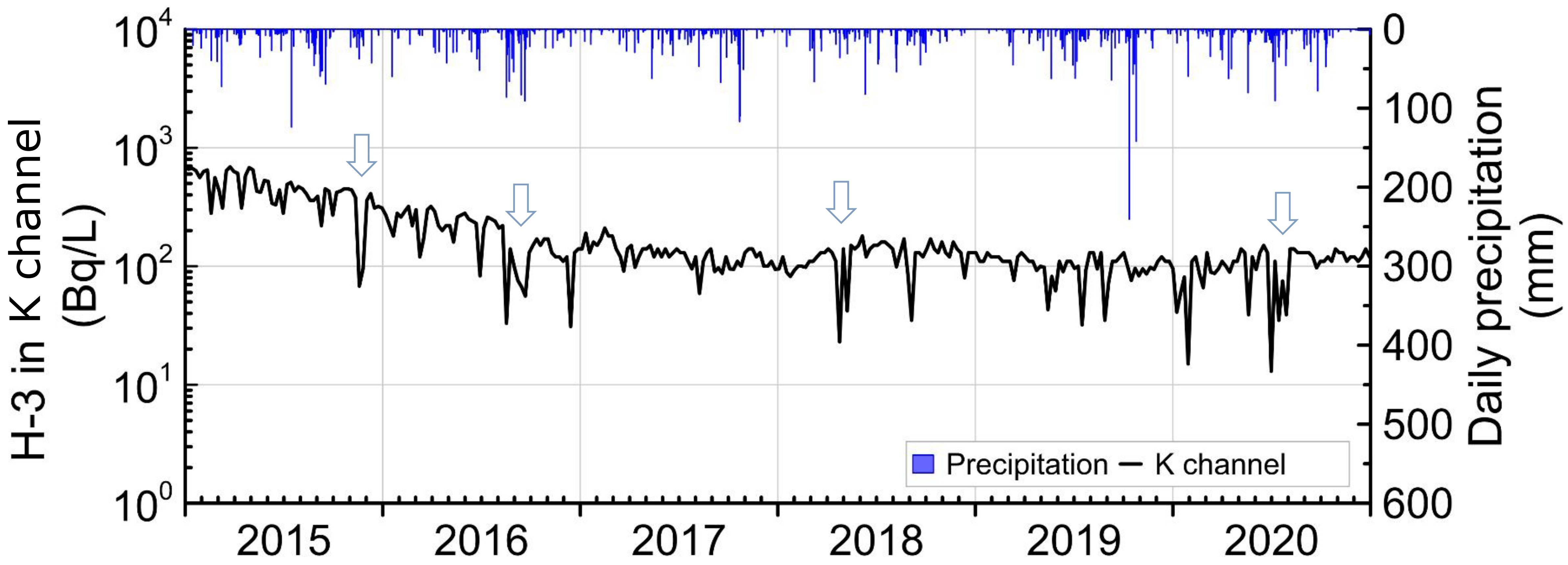


Fig. Variation of ^{3}H concentrations in the K drainage channel from 2015-2020 with respect to rainfall

1. K drainage ^{3}H concentrations decrease with rain.
2. The water entering the K drainage channel is a mixture of two types.

Leaking ^{3}H from the tank can be used as a tracer.

⇒The percentage of surface flow of rainfall origin can be calculated. (Applied to runoff analysis)

(Result) Determine endmembers from groundwater bypass concentrations

- How to determine tritium endmembers? →Use groundwater bypass concentrations distributed upstream north and south of drainage channel K.

<u>Groundwater bypass</u>: 12 wells installed to lower the groundwater level upstream.

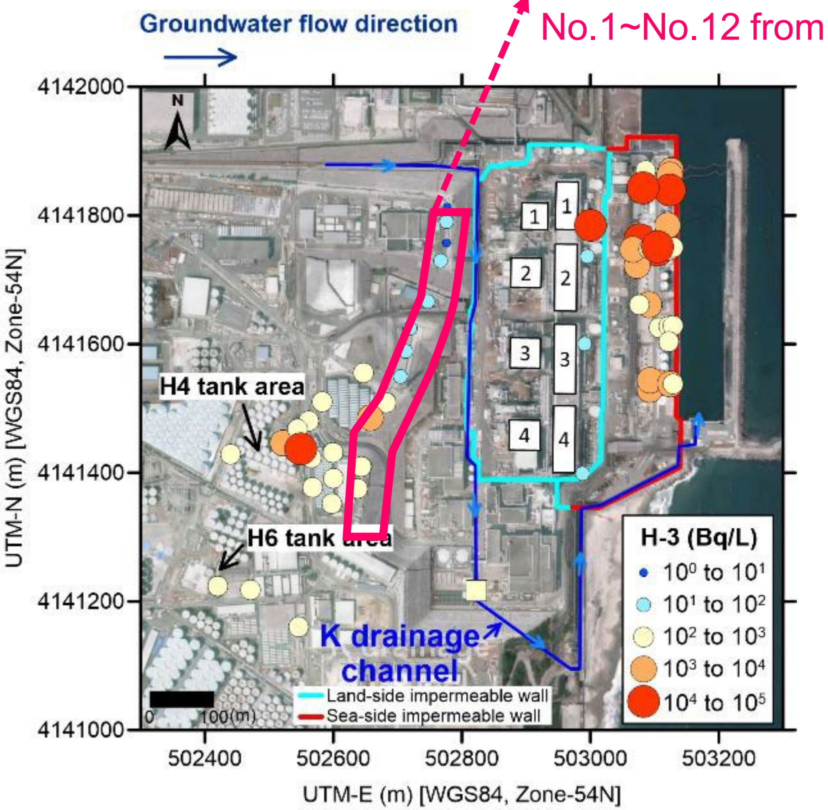
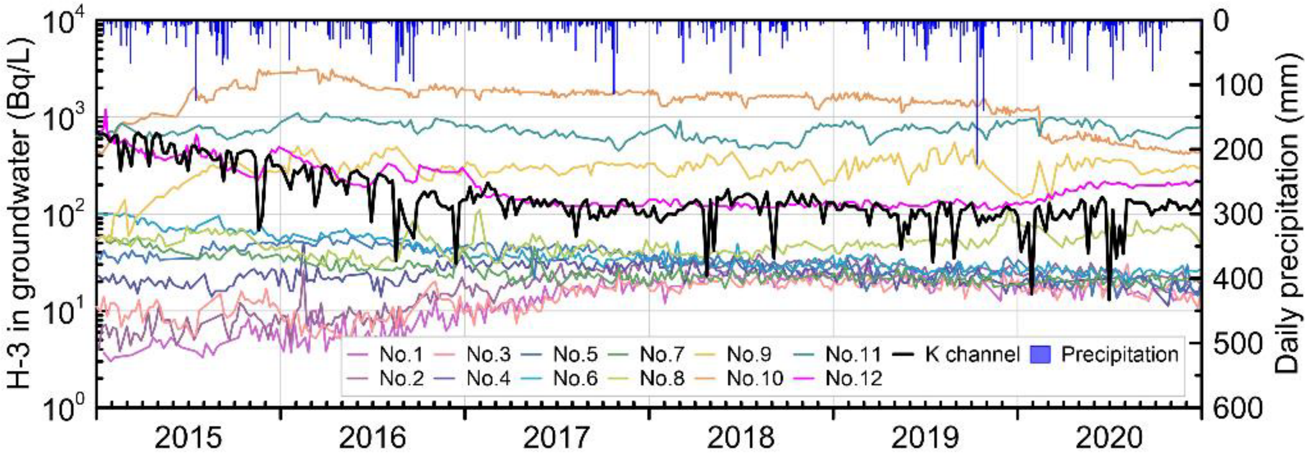


Fig. 2016 average tritium concentrations in groundwater (●) and in drainage channel K (■). Background is from GSI (taken in 2018).



Variation of ^{3}H concentrations in groundwater bypass and K drainage channels during 2015-2020

<u>Concentration of groundwater bypass No.1 to No.12 is weighted 50% for No.12 only and the rest is further weighted by effluent ratio.</u>

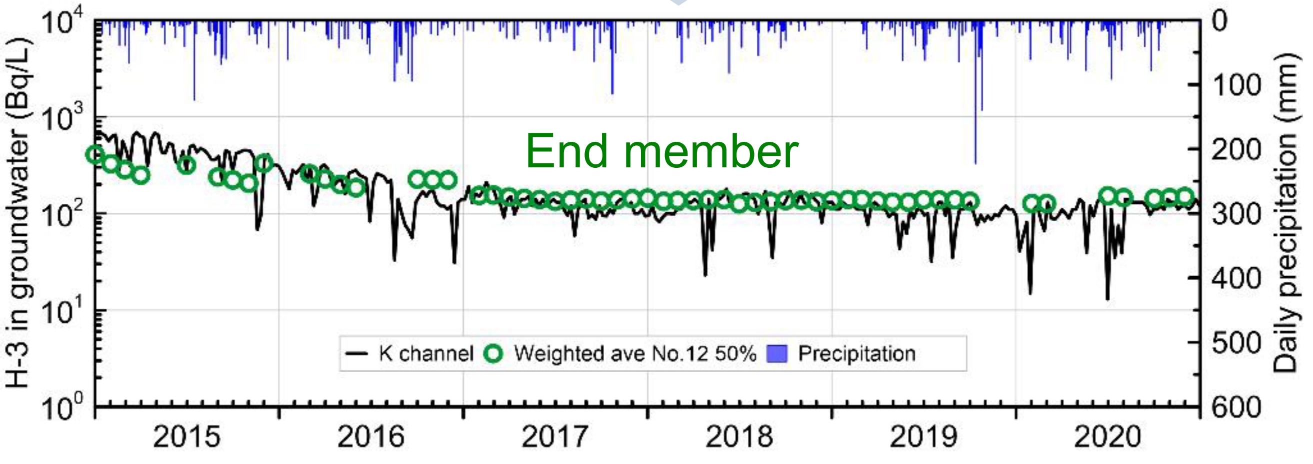


Fig. End member and K drainage ^{3}H concentrations in 2015-2020

(Result) Tritium tracer is used to determine the contribution of surface flow

binary mixing model

$$QC_d = Q_bC_b + Q_sC_s$$

$$C_d = \frac{Q_b}{Q_d}C_b + \frac{Q_s}{Q_d}C_s$$

$$F_b = \frac{Q_b}{Q_d}, \quad F_s = \frac{Q_s}{Q_d}$$

$$\boldsymbol{C_d = F_bC_b + F_sC_s}$$

Tritium concentration in drainage channel K (C_d)

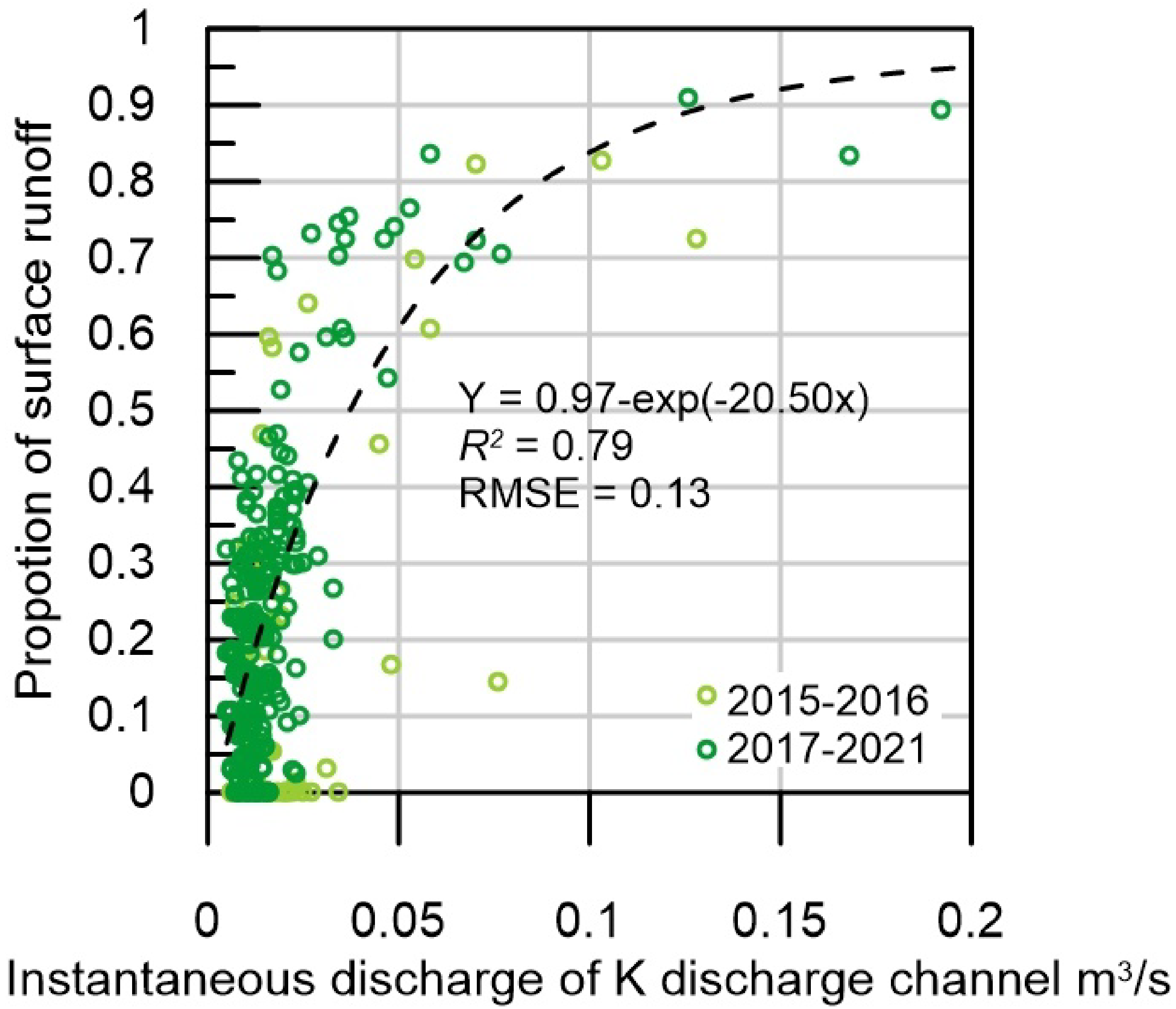
Tritium concentration in groundwater (C_b)

Tritium concentration in precipitation (C_s)

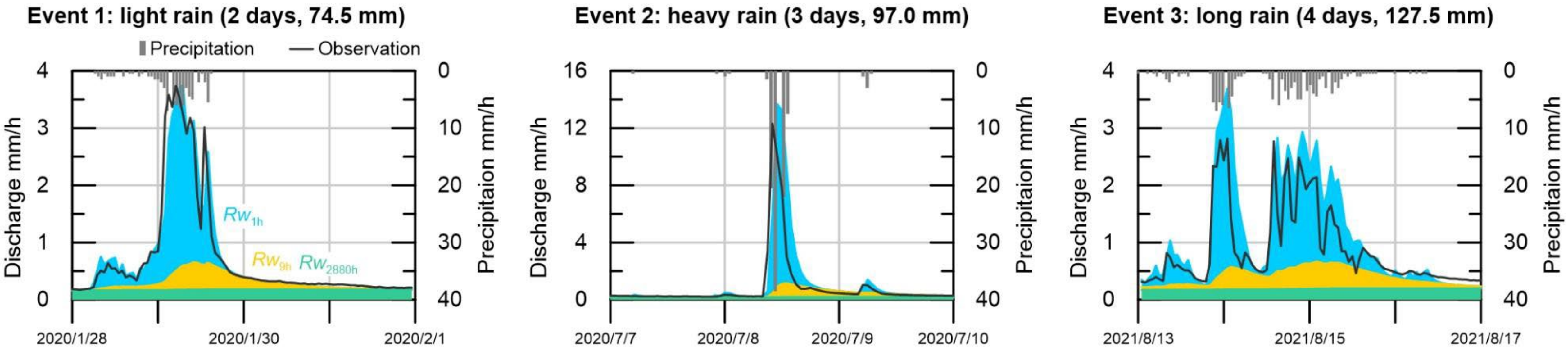
F_b: Rate of groundwater flow
F_s: Percentage of surface flow

C_d: ^{3}H concentrations in drainage channel K
C_b: ^{3}H concentrations in groundwater flow (end member)
C_s: ^{3}H concentrations in precipitation (0.33 Bq/L: 2016 annual average in Fukushima, Gusyev et al. 2019)

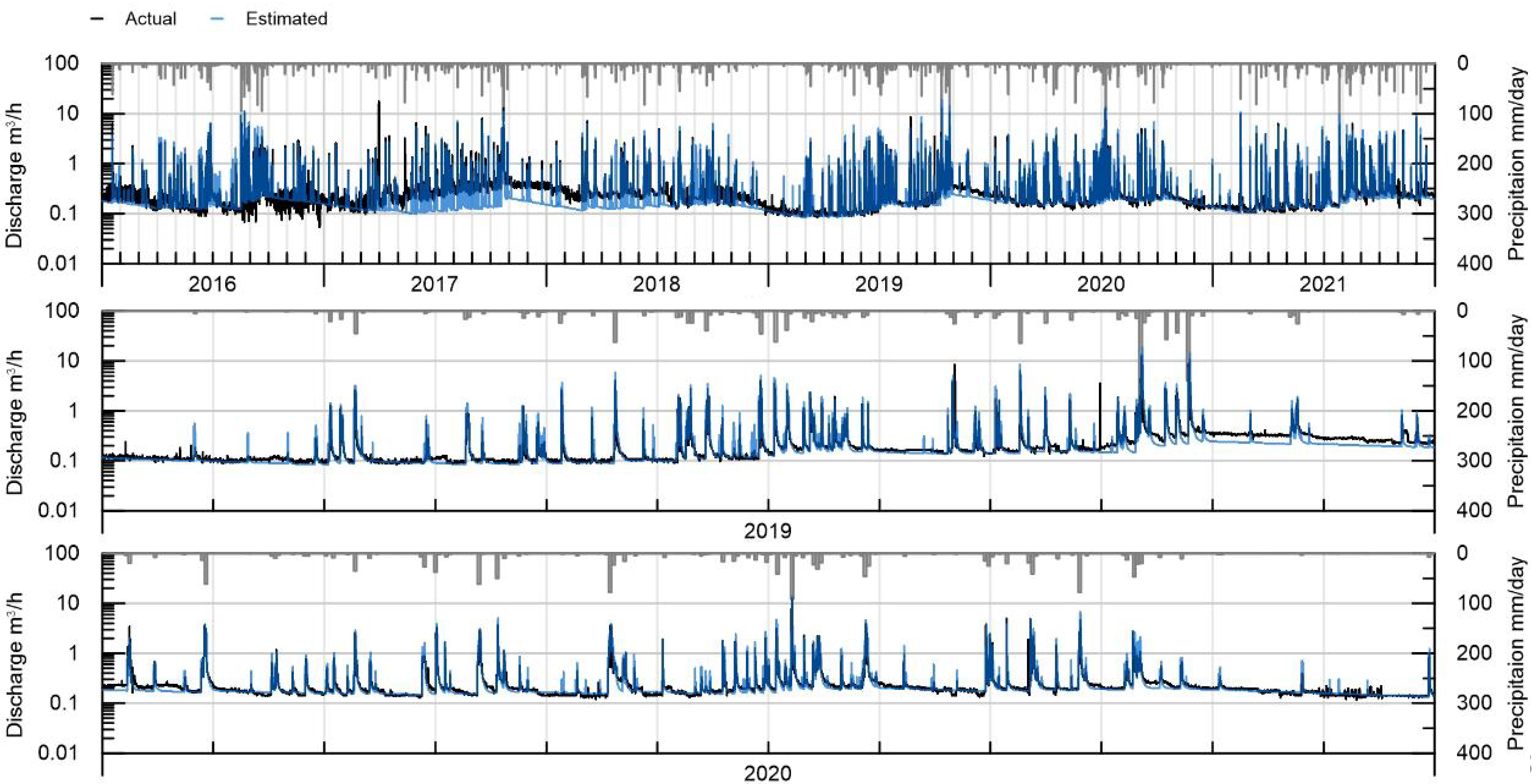
(Result) Contribution of surface flow vs. flow rate in K drainage channel



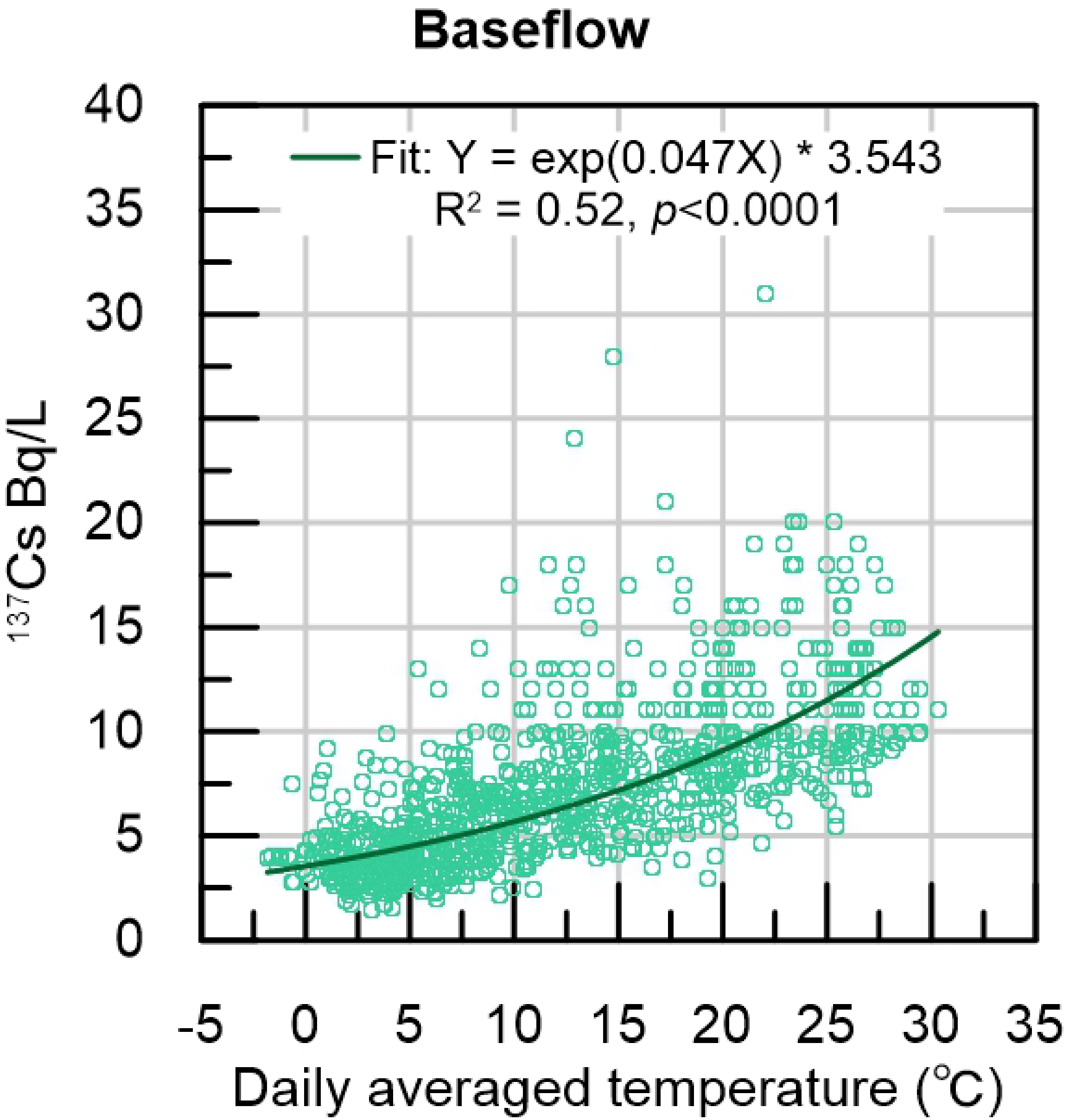
Estimation of flow rates for each runoff component using effective rainfall (Rw) (3 rainfall events)



K drainage channel flow estimated by effective rainfall



Concentration of ^{137}Cs in the baseflow vs. temperature



Endmember concentrations

Base flow

C=3.543 $^{0.047*T}$

Surface runoff

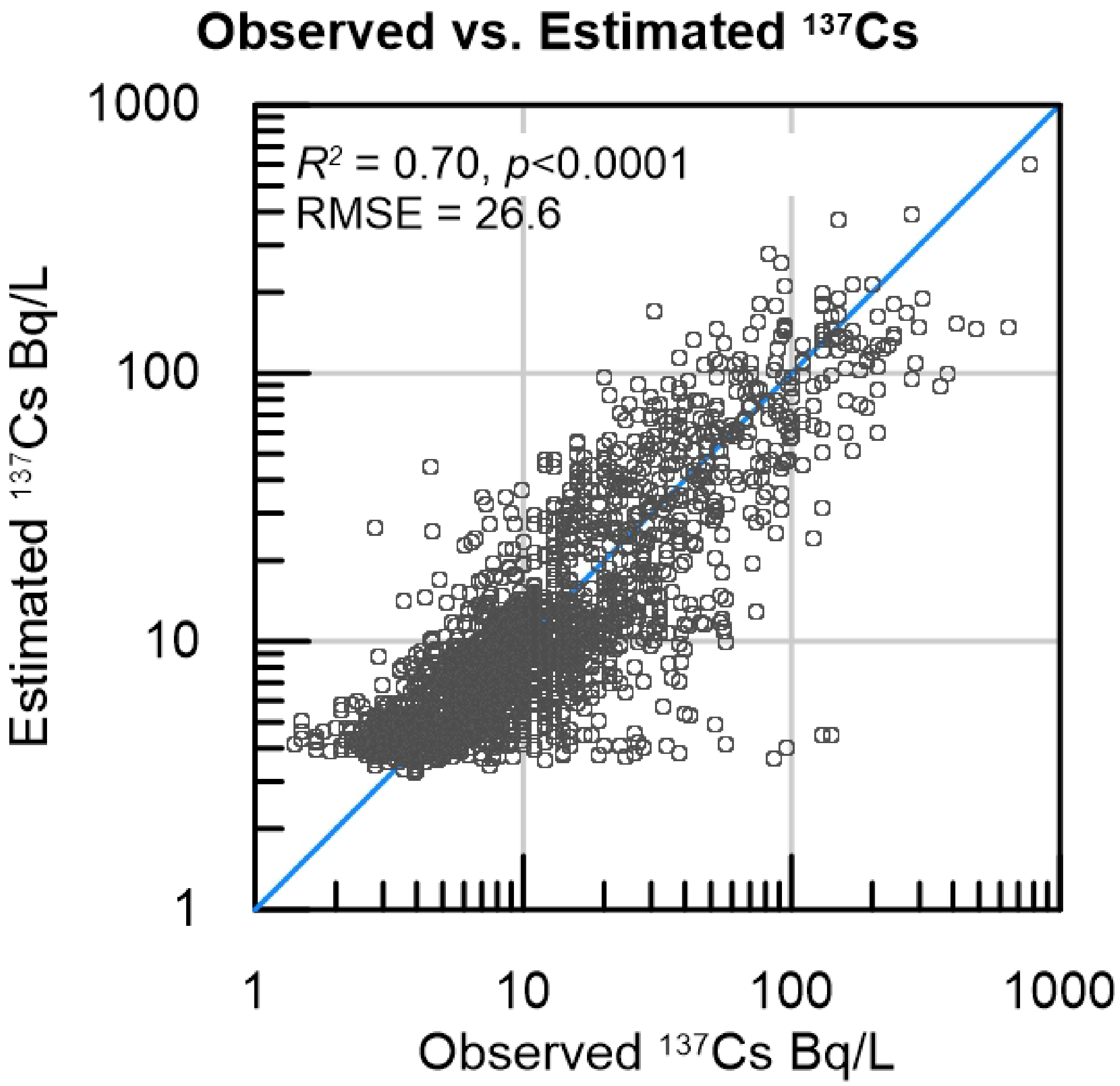
C= 50.1*$Q^{0.6}$

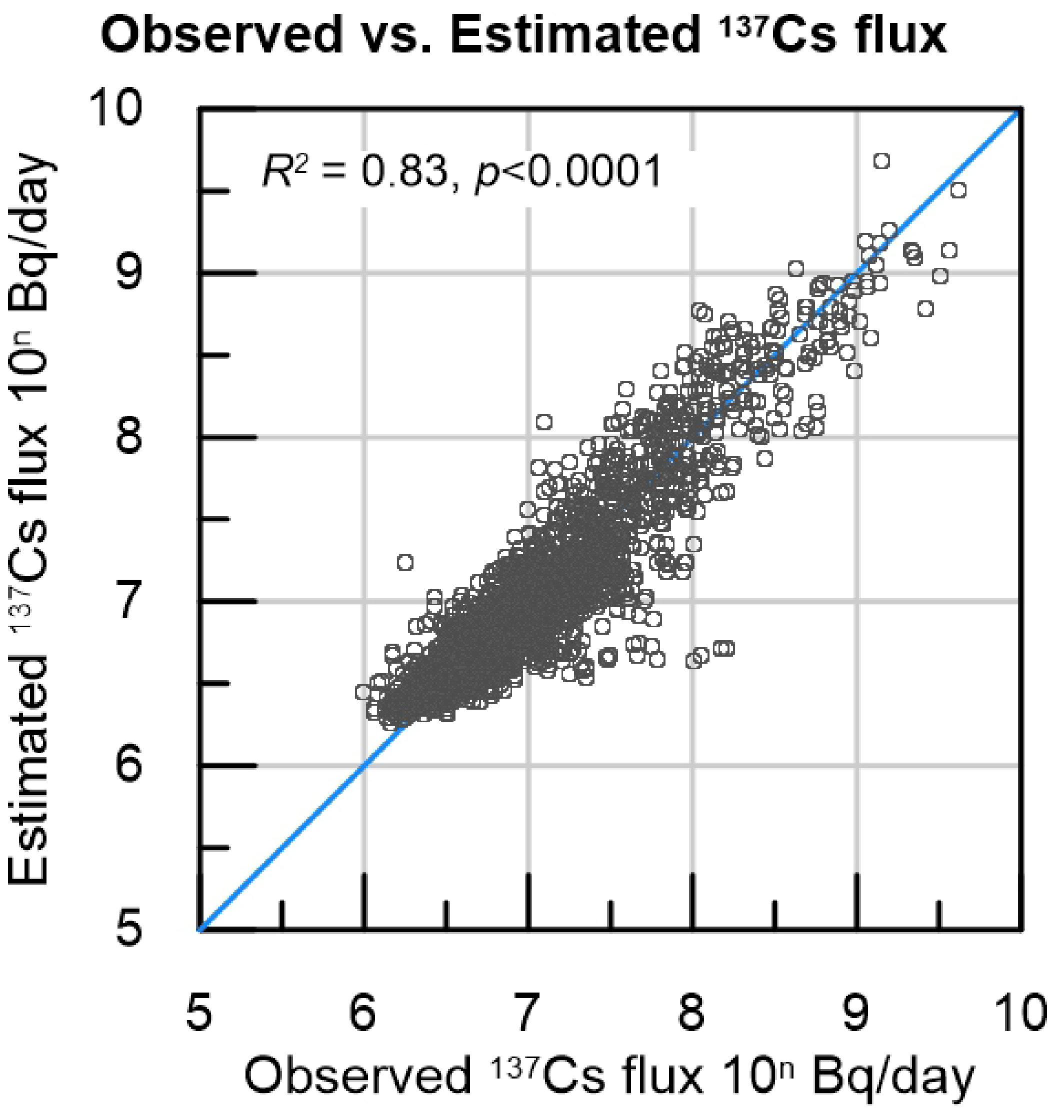
Roof drainage

C=658.2*$Q^{0.6}$

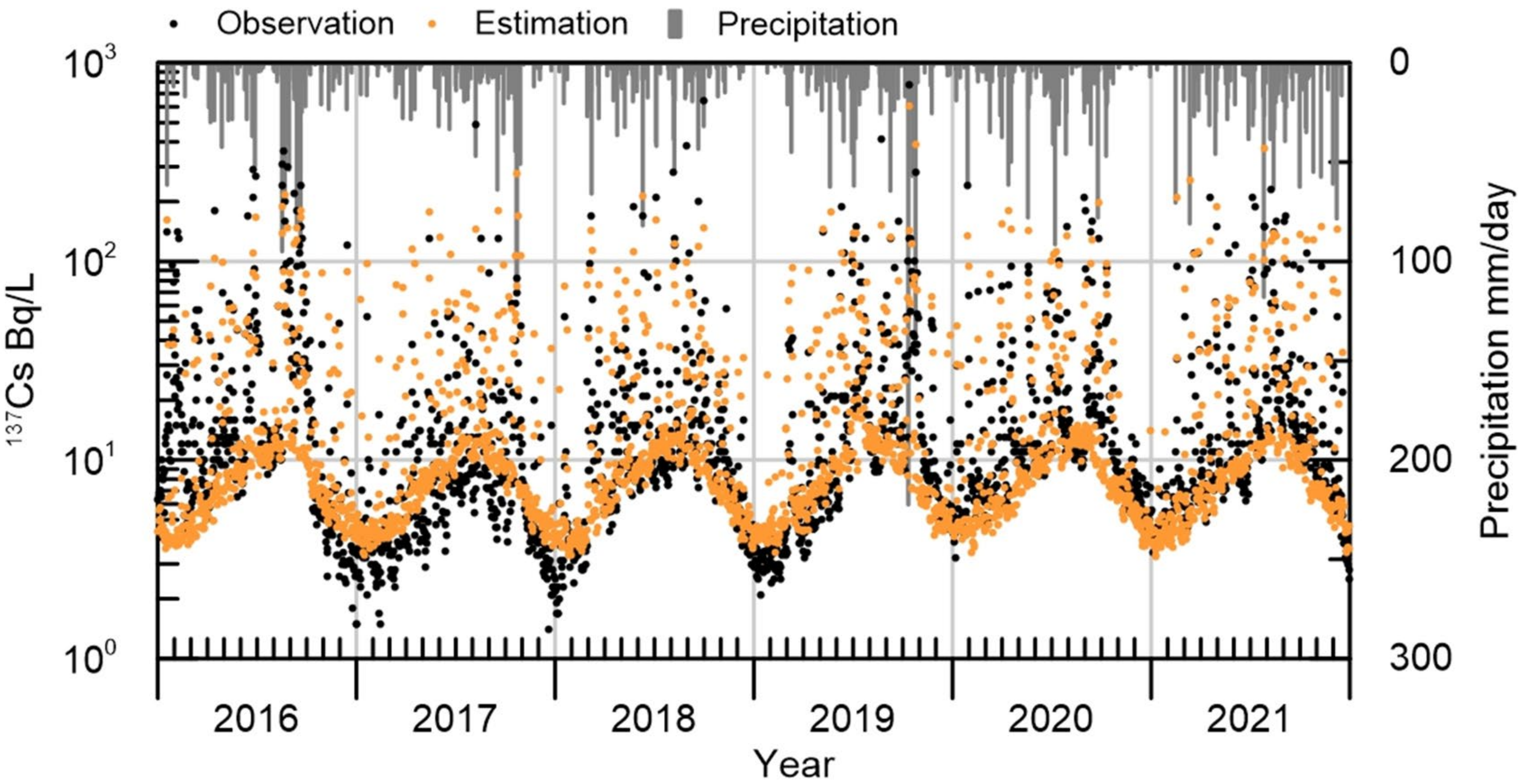
T:Temperature, Q discharge m^3/s

Measured vs. estimated ^{137}Cs concentrations and ^{137}Cs fluxes

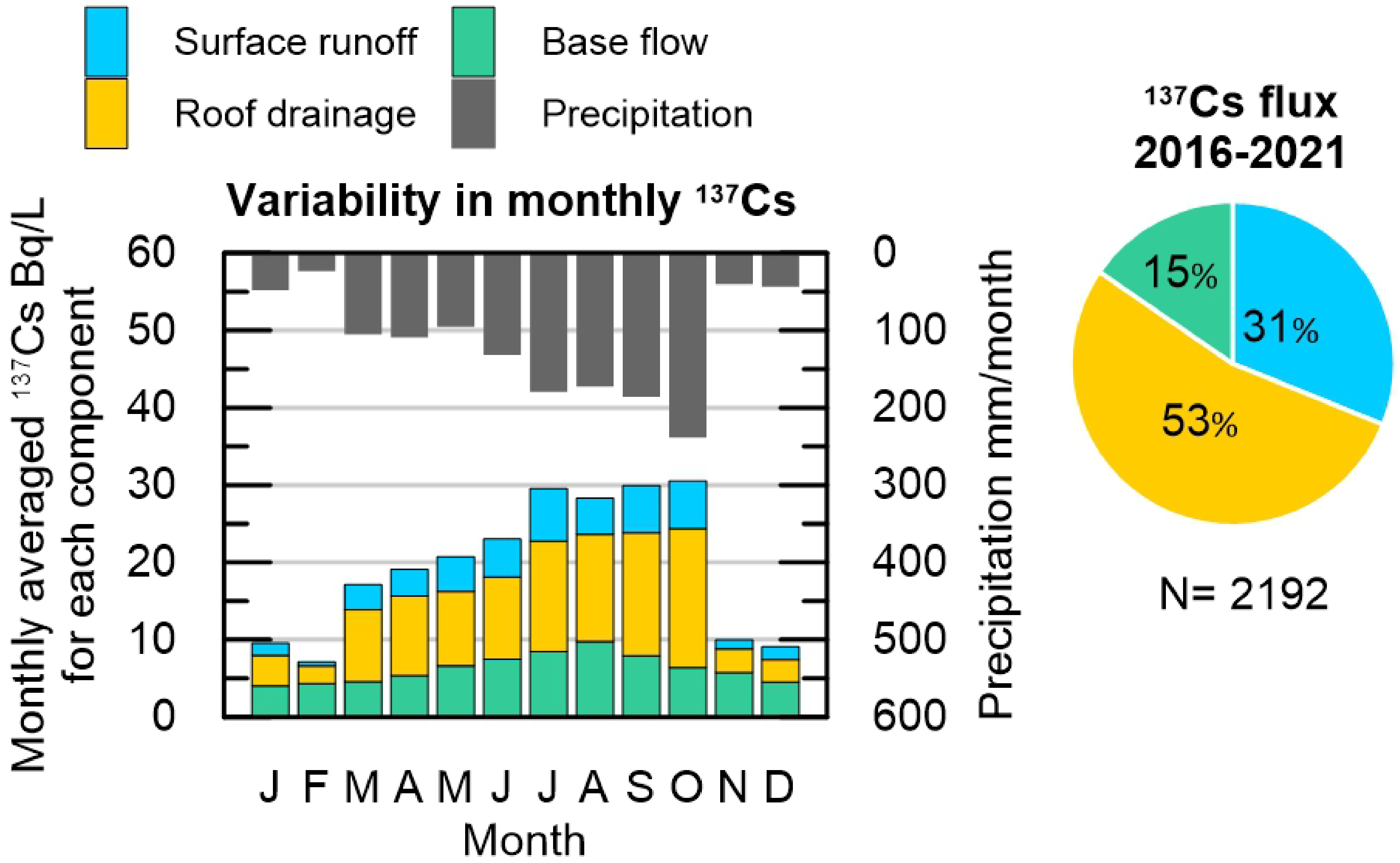




^{137}Measured vs. estimated Cs concentration

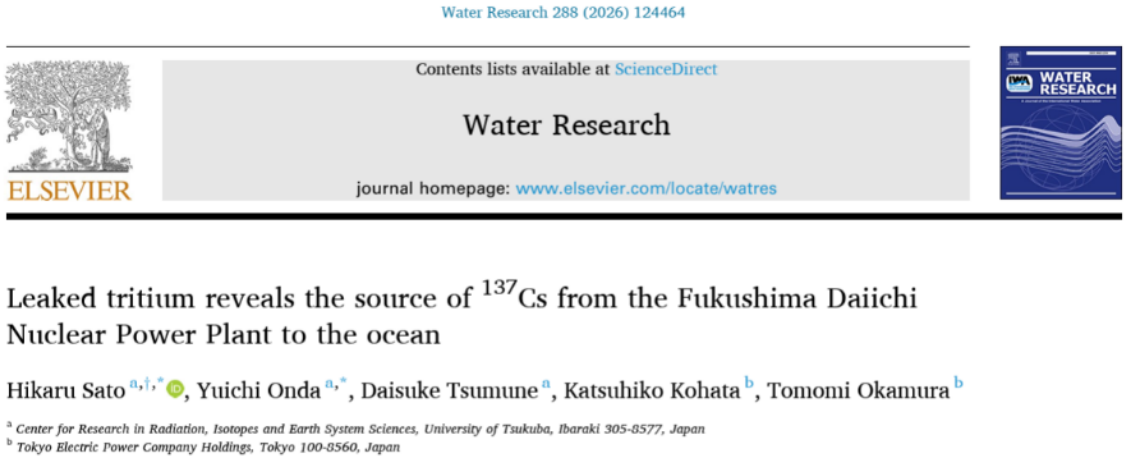


Monthly ^{137}Cs concentrations and 2016-2021 flux ratios for each runoff component



Conclusion

We found that the primary source of ^{137}Cs is the roofs of the reactor buildings, with high residual concentrations significantly influencing the flux in the channel. Seasonal variations are linked to the effects of temperature on ^{137}Cs in base flow and rainfall-driven spikes in surface runoff and structural inflow.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Leaked tritium reveals the source of ^{137}Cs from the Fukushima Daiichi Nuclear Power Plant to the ocean

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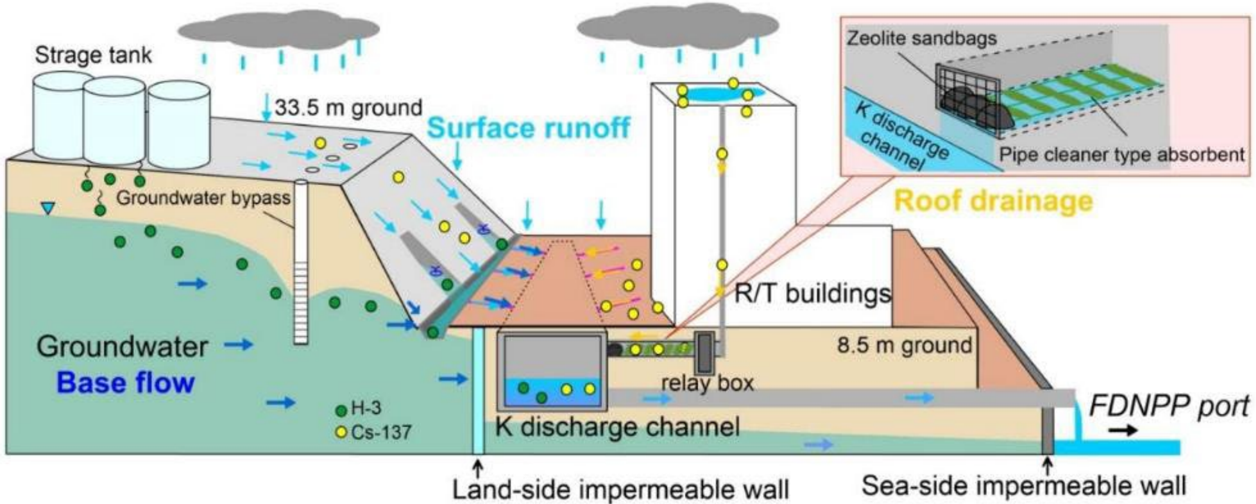
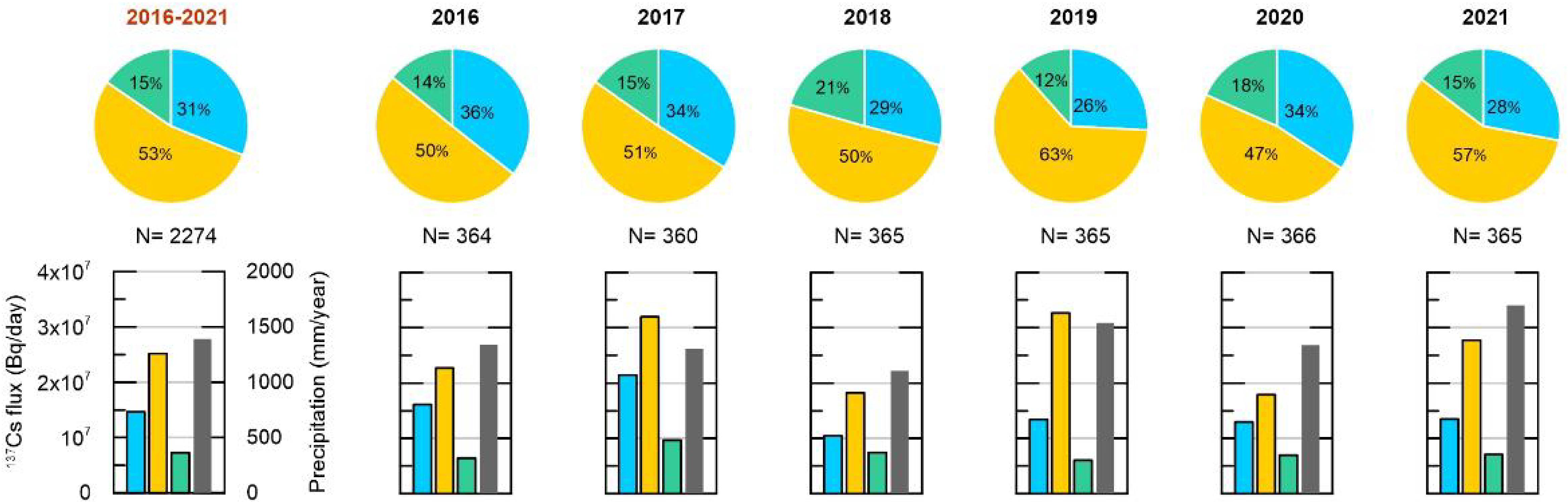


By year ^{137}Cs Flux

Yearly averaged ^{137}Cs flux Bq/day	2016-2021	2016	2017	2018	2019	2020	2021
Surface runoff	1.47×10^7	1.61×10^7	2.14×10^7	1.05×10^7	1.35×10^7	1.30×10^7	1.35×10^7
Roof drainage	2.52×10^7	2.27×10^7	3.20×10^7	1.83×10^7	3.26×10^7	1.79×10^7	2.77×10^7
Base flow	7.26×10^6	6.42×10^6	9.64×10^6	7.43×10^6	6.04×10^7	6.95×10^6	7.08×10^6
Total	4.71×10^7	4.53×10^7	6.30×10^7	3.62×10^7	5.21×10^7	3.78×10^7	4.83×10^7
Precipitation (mm/year)	1391	1343	1309	1112	1543	1341	1701



Research Subjects and Analysis Data

- subject of research

K drainage channel at Fukushima Daiichi Nuclear Power Plant data

Seawater in harbors: Surface water was collected in buckets at a total of 9 sites.

2. drainage channel K: 1 point, timed water sampling by automatic water sampler (ISCO 6712: ISCO, Inc., USA). The flow rate was determined by taken every 10 minutes immediately upstream and are calculated from water level and velocity measurements with a weir.

3. groundwater: (groundwater bypass, sub-drain) Pumped water was collected from the sampling line.

(Tank area) Water sampler, (2.5m bed groundwater) water sampling pump.

Rainfall: Measured by a tipping over rain gauge on the site.

5. measurement of radioactive materials:
Cs Seawater and groundwater in harbors: Measured directly in marinelli containers with Ge semiconductor detectors.

Total β Sample 10cc was pretreated by evaporation and solidification method, and then measured by linear beam chromatography (LBC).

Tritium The sample, which has had impurities removed by distillation, is mixed with the scintillator, and then the liquid scintillation cow is mixed with the scintillator.

The data was measured by a computer.

These data were collected from publicly available data on the TEPCO website (https://www.tepco.co.jp/decommission/data/analysis/) and with the cooperation of TEPCO personnel.