Setup and Imports

```
!pip install rasterio segmentation-models-pytorch
```

```
Collecting rasterio
  Downloading rasterio-1.4.3-cp311-cp311-
manylinux_2_17_x86_64.manylinux2014_x86_64.whl.metadata (9.1 kB)
Collecting segmentation-models-pytorch
  Downloading segmentation_models_pytorch-0.5.0-py3-none-
any.whl.metadata (17 kB)
Collecting affine (from rasterio)
  Downloading affine-2.4.0-py3-none-any.whl.metadata (4.0 kB)
Requirement already satisfied: attrs in
/usr/local/lib/python3.11/dist-packages (from rasterio) (25.3.0)
Requirement already satisfied: certifi in
/usr/local/lib/python3.11/dist-packages (from rasterio) (2025.4.26)
Requirement already satisfied: click>=4.0 in
/usr/local/lib/python3.11/dist-packages (from rasterio) (8.2.0)
Collecting cligj>=0.5 (from rasterio)
  Downloading cligj-0.7.2-py3-none-any.whl.metadata (5.0 kB)
Requirement already satisfied: numpy>=1.24 in
/usr/local/lib/python3.11/dist-packages (from rasterio) (2.0.2)
Collecting click-plugins (from rasterio)
  Downloading click_plugins-1.1.1-py2.py3-none-any.whl.metadata (6.4
kB)
Requirement already satisfied: pyparsing in
/usr/local/lib/python3.11/dist-packages (from rasterio) (3.2.3)
Requirement already satisfied: huggingface-hub>=0.24 in
/usr/local/lib/python3.11/dist-packages (from segmentation-models-
pytorch) (0.31.2)
Requirement already satisfied: pillow>=8 in
/usr/local/lib/python3.11/dist-packages (from segmentation-models-
pytorch) (11.2.1)
Requirement already satisfied: safetensors>=0.3.1 in
/usr/local/lib/python3.11/dist-packages (from segmentation-models-
pytorch) (0.5.3)
Requirement already satisfied: timm>=0.9 in
/usr/local/lib/python3.11/dist-packages (from segmentation-models-
pytorch) (1.0.15)
Requirement already satisfied: torch>=1.8 in
/usr/local/lib/python3.11/dist-packages (from segmentation-models-
pytorch) (2.6.0+cu124)
Requirement already satisfied: torchvision>=0.9 in
/usr/local/lib/python3.11/dist-packages (from segmentation-models-
pytorch) (0.21.0+cu124)
Requirement already satisfied: tqdm>=4.42.1 in
/usr/local/lib/python3.11/dist-packages (from segmentation-models-
pytorch) (4.67.1)
```

```
Requirement already satisfied: filelock in
/usr/local/lib/python3.11/dist-packages (from huggingface-hub>=0.24-
>segmentation-models-pytorch) (3.18.0)
Requirement already satisfied: fsspec>=2023.5.0 in
/usr/local/lib/python3.11/dist-packages (from huggingface-hub>=0.24-
>segmentation-models-pytorch) (2025.3.2)
Requirement already satisfied: packaging>=20.9 in
/usr/local/lib/python3.11/dist-packages (from huggingface-hub>=0.24-
>segmentation-models-pytorch) (24.2)
Requirement already satisfied: pyyaml>=5.1 in
/usr/local/lib/python3.11/dist-packages (from huggingface-hub>=0.24-
>segmentation-models-pytorch) (6.0.2)
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>segmentation-models-pytorch) (2.32.3)
Requirement already satisfied: typing-extensions>=3.7.4.3 in
/usr/local/lib/python3.11/dist-packages (from huggingface-hub>=0.24-
>segmentation-models-pytorch) (4.13.2)
Requirement already satisfied: networkx in
/usr/local/lib/python3.11/dist-packages (from torch>=1.8-
>segmentation-models-pytorch) (3.4.2)
Requirement already satisfied: jinja2 in
/usr/local/lib/python3.11/dist-packages (from torch>=1.8-
>segmentation-models-pytorch) (3.1.6)
Collecting nvidia-cuda-nvrtc-cu12==12.4.127 (from torch>=1.8-
>segmentation-models-pytorch)
  Downloading nvidia_cuda_nvrtc_cu12-12.4.127-py3-none-
manylinux2014_x86_64.whl.metadata (1.5 kB)
Collecting nvidia-cuda-runtime-cu12==12.4.127 (from torch>=1.8-
>segmentation-models-pytorch)
  Downloading nvidia_cuda_runtime_cu12-12.4.127-py3-none-
manylinux2014_x86_64.whl.metadata (1.5 kB)
Collecting nvidia-cuda-cupti-cu12==12.4.127 (from torch>=1.8-
>segmentation-models-pytorch)
  Downloading nvidia_cuda_cupti_cu12-12.4.127-py3-none-
manylinux2014_x86_64.whl.metadata (1.6 kB)
Collecting nvidia-cudnn-cu12==9.1.0.70 (from torch>=1.8->segmentation-
models-pytorch)
  Downloading nvidia_cudnn_cu12-9.1.0.70-py3-none-
manylinux2014_x86_64.whl.metadata (1.6 kB)
Collecting nvidia-cublas-cu12==12.4.5.8 (from torch>=1.8-
>segmentation-models-pytorch)
  Downloading nvidia_cublas_cu12-12.4.5.8-py3-none-
manylinux2014_x86_64.whl.metadata (1.5 kB)
Collecting nvidia-cufft-cu12==11.2.1.3 (from torch>=1.8->segmentation-
models-pytorch)
  Downloading nvidia_cufft_cu12-11.2.1.3-py3-none-
manylinux2014_x86_64.whl.metadata (1.5 kB)
Collecting nvidia-curand-cu12==10.3.5.147 (from torch>=1.8-
>segmentation-models-pytorch)
  Downloading nvidia_curand_cu12-10.3.5.147-py3-none-
manylinux2014_x86_64.whl.metadata (1.5 kB)
Collecting nvidia-cusolver-cu12==11.6.1.9 (from torch>=1.8-
>segmentation-models-pytorch)
  Downloading nvidia_cusolver_cu12-11.6.1.9-py3-none-
manylinux2014_x86_64.whl.metadata (1.6 kB)
Collecting nvidia-cusparse-cu12==12.3.1.170 (from torch>=1.8-
>segmentation-models-pytorch)
  Downloading nvidia_cusparse_cu12-12.3.1.170-py3-none-
manylinux2014_x86_64.whl.metadata (1.6 kB)
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/usr/local/lib/python3.11/dist-packages (from torch>=1.8-
>segmentation-models-pytorch) (0.6.2)
Requirement already satisfied: nvidia-nccl-cu12==2.21.5 in
/usr/local/lib/python3.11/dist-packages (from torch>=1.8-
>segmentation-models-pytorch) (2.21.5)
Requirement already satisfied: nvidia-nvtx-cu12==12.4.127 in
/usr/local/lib/python3.11/dist-packages (from torch>=1.8-
>segmentation-models-pytorch) (12.4.127)
Collecting nvidia-nvjitlink-cu12==12.4.127 (from torch>=1.8-
>segmentation-models-pytorch)
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>segmentation-models-pytorch) (3.2.0)
Requirement already satisfied: sympy==1.13.1 in
/usr/local/lib/python3.11/dist-packages (from torch>=1.8-
>segmentation-models-pytorch) (1.13.1)
Requirement already satisfied: mpmath<1.4,>=1.1.0 in
/usr/local/lib/python3.11/dist-packages (from sympy==1.13.1-
>torch>=1.8->segmentation-models-pytorch) (1.3.0)
Requirement already satisfied: MarkupSafe>=2.0 in
/usr/local/lib/python3.11/dist-packages (from jinja2->torch>=1.8-
>segmentation-models-pytorch) (3.0.2)
Requirement already satisfied: charset-normalizer<4,>=2 in
/usr/local/lib/python3.11/dist-packages (from requests->huggingface-
hub>=0.24->segmentation-models-pytorch) (3.4.2)
Requirement already satisfied: idna<4,>=2.5 in
/usr/local/lib/python3.11/dist-packages (from requests->huggingface-
hub>=0.24->segmentation-models-pytorch) (3.10)
Requirement already satisfied: urllib3<3,>=1.21.1 in
/usr/local/lib/python3.11/dist-packages (from requests->huggingface-
hub>=0.24->segmentation-models-pytorch) (2.4.0)
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manylinux_2_17_x86_64.manylinux2014_x86_64.whl (22.2 MB)
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entation_models_pytorch-0.5.0-py3-none-any.whl (154 kB)
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anylinux2014_x86_64.whl (363.4 MB)
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anylinux2014_x86_64.whl (13.8 MB)
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anylinux2014_x86_64.whl (664.8 MB)
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anylinux2014_x86_64.whl (211.5 MB)
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anylinux2014_x86_64.whl (127.9 MB)
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anylinux2014_x86_64.whl (207.5 MB)
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anylinux2014_x86_64.whl (21.1 MB)
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0:00:00
e-cu12, nvidia-cuda-nvrtc-cu12, nvidia-cuda-cupti-cu12, nvidia-cublas-
cu12, cligj, click-plugins, affine, rasterio, nvidia-cusparse-cu12,
nvidia-cudnn-cu12, nvidia-cusolver-cu12, segmentation-models-pytorch
  Attempting uninstall: nvidia-nvjitlink-cu12
    Found existing installation: nvidia-nvjitlink-cu12 12.5.82
    Uninstalling nvidia-nvjitlink-cu12-12.5.82:
      Successfully uninstalled nvidia-nvjitlink-cu12-12.5.82
  Attempting uninstall: nvidia-curand-cu12
    Found existing installation: nvidia-curand-cu12 10.3.6.82
    Uninstalling nvidia-curand-cu12-10.3.6.82:
      Successfully uninstalled nvidia-curand-cu12-10.3.6.82
  Attempting uninstall: nvidia-cufft-cu12
    Found existing installation: nvidia-cufft-cu12 11.2.3.61
    Uninstalling nvidia-cufft-cu12-11.2.3.61:
      Successfully uninstalled nvidia-cufft-cu12-11.2.3.61
  Attempting uninstall: nvidia-cuda-runtime-cu12
```

```
    Found existing installation: nvidia-cuda-runtime-cu12 12.5.82
    Uninstalling nvidia-cuda-runtime-cu12-12.5.82:
      Successfully uninstalled nvidia-cuda-runtime-cu12-12.5.82
  Attempting uninstall: nvidia-cuda-nvrtc-cu12
    Found existing installation: nvidia-cuda-nvrtc-cu12 12.5.82
    Uninstalling nvidia-cuda-nvrtc-cu12-12.5.82:
      Successfully uninstalled nvidia-cuda-nvrtc-cu12-12.5.82
  Attempting uninstall: nvidia-cuda-cupti-cu12
    Found existing installation: nvidia-cuda-cupti-cu12 12.5.82
    Uninstalling nvidia-cuda-cupti-cu12-12.5.82:
      Successfully uninstalled nvidia-cuda-cupti-cu12-12.5.82
  Attempting uninstall: nvidia-cublas-cu12
    Found existing installation: nvidia-cublas-cu12 12.5.3.2
    Uninstalling nvidia-cublas-cu12-12.5.3.2:
      Successfully uninstalled nvidia-cublas-cu12-12.5.3.2
  Attempting uninstall: nvidia-cusparse-cu12
    Found existing installation: nvidia-cusparse-cu12 12.5.1.3
    Uninstalling nvidia-cusparse-cu12-12.5.1.3:
      Successfully uninstalled nvidia-cusparse-cu12-12.5.1.3
  Attempting uninstall: nvidia-cudnn-cu12
    Found existing installation: nvidia-cudnn-cu12 9.3.0.75
    Uninstalling nvidia-cudnn-cu12-9.3.0.75:
      Successfully uninstalled nvidia-cudnn-cu12-9.3.0.75
  Attempting uninstall: nvidia-cusolver-cu12
    Found existing installation: nvidia-cusolver-cu12 11.6.3.83
    Uninstalling nvidia-cusolver-cu12-11.6.3.83:
      Successfully uninstalled nvidia-cusolver-cu12-11.6.3.83
Successfully installed affine-2.4.0 click-plugins-1.1.1 cligj-0.7.2
nvidia-cublas-cu12-12.4.5.8 nvidia-cuda-cupti-cu12-12.4.127 nvidia-
cuda-nvrtc-cu12-12.4.127 nvidia-cuda-runtime-cu12-12.4.127 nvidia-
cudnn-cu12-9.1.0.70 nvidia-cufft-cu12-11.2.1.3 nvidia-curand-cu12-
10.3.5.147 nvidia-cusolver-cu12-11.6.1.9 nvidia-cusparse-cu12-
12.3.1.170 nvidia-nvjitlink-cu12-12.4.127 rasterio-1.4.3 segmentation-
models-pytorch-0.5.0
```

```python
import os
import numpy as np
import matplotlib.pyplot as plt
import rasterio as rio
from sklearn.model_selection import train_test_split
from sklearn.metrics import mean_absolute_error, mean_squared_error,
r2_score

import torch
from torch.utils.data import TensorDataset, DataLoader
from torch import nn
import segmentation_models_pytorch as smp

# Paths
```

```
base_path = "/content/drive/MyDrive/Final Tif Files "
NODATA_VAL = -9999
```

Utility Functions

```
def load_and_prepare(composite_path, vnl_path=None):
    with rio.open(composite_path) as src:
        X = src.read().astype(np.float32)
        meta = src.meta.copy()
    X[X == NODATA_VAL] = np.nan
    for b in range(X.shape[0]):
        band = X[b]
        min_val, max_val = np.nanmin(band), np.nanmax(band)
        if max_val > min_val:
            X[b] = (band - min_val) / (max_val - min_val)
    if vnl_path:
        with rio.open(vnl_path) as src:
            y = src.read(1).astype(np.float32)
        y[y == NODATA_VAL] = np.nan
        return X, y, meta
    return X, None, meta

def create_valid_tiles(X, y, tile_size=128, stride=64):
    H, W = y.shape
    X_tiles, y_tiles = [], []
    for i in range(0, H - tile_size + 1, stride):
        for j in range(0, W - tile_size + 1, stride):
            x_patch = X[:, i:i+tile_size, j:j+tile_size]
            y_patch = y[i:i+tile_size, j:j+tile_size]
            if np.isnan(x_patch).any() or np.isnan(y_patch).any():
                continue
            X_tiles.append(np.moveaxis(x_patch, 0, -1))
            y_tiles.append(y_patch[..., np.newaxis])
    return np.array(X_tiles), np.array(y_tiles)
```

DeepLabV3+ Model Setup & Training (Cairo 2021)

```
# Load and tile 2021 data
file_train_X = os.path.join(base_path,
"Composite_Cairo_Train_2021_cleaned.tif")
file_train_y = os.path.join(base_path, "VNL_Cairo_2021_Final.tif")
X_raw, y_raw, _ = load_and_prepare(file_train_X, file_train_y)
X_tiles, y_tiles = create_valid_tiles(X_raw, y_raw)
```

```
X_train, X_val, y_train, y_val = train_test_split(X_tiles, y_tiles,
test_size=0.2, random_state=42)
X_train_tensor = torch.tensor(X_train.transpose(0, 3, 1, 2),
dtype=torch.float32)
y_train_tensor = torch.tensor(y_train, dtype=torch.float32).squeeze(3)
X_val_tensor = torch.tensor(X_val.transpose(0, 3, 1, 2),
dtype=torch.float32)
y_val_tensor = torch.tensor(y_val, dtype=torch.float32).squeeze(3)

train_loader = DataLoader(TensorDataset(X_train_tensor,
y_train_tensor), batch_size=8, shuffle=True)
val_loader = DataLoader(TensorDataset(X_val_tensor, y_val_tensor),
batch_size=8)

device = torch.device("cuda" if torch.cuda.is_available() else "cpu")

model = smp.DeepLabV3Plus(
    encoder_name="resnet34",
    encoder_weights="imagenet",
    in_channels=12,
    classes=1,
    activation=None
).to(device)

criterion = nn.MSELoss()
optimizer = torch.optim.Adam(model.parameters(), lr=1e-4)

train_losses, val_losses = [], []

def train_deeplab(model, train_loader, val_loader, epochs=20):
    for epoch in range(epochs):
        model.train()
        train_loss, val_loss = 0, 0
        for xb, yb in train_loader:
            xb, yb = xb.to(device), yb.to(device)
            optimizer.zero_grad()
            preds = model(xb).squeeze(1)
            loss = criterion(preds, yb)
            loss.backward()
            optimizer.step()
            train_loss += loss.item()
        train_losses.append(train_loss / len(train_loader))

        model.eval()
        with torch.no_grad():
            for xb, yb in val_loader:
                xb, yb = xb.to(device), yb.to(device)
                preds = model(xb).squeeze(1)
                val_loss += criterion(preds, yb).item()
        val_losses.append(val_loss / len(val_loader))
```

```python
        print(f"Epoch {epoch+1}/{epochs} – Train Loss: {train_losses[-1]:.4f}, Val Loss: {val_losses[-1]:.4f}")

train_deeplab(model, train_loader, val_loader, epochs=30)
```

```
/usr/local/lib/python3.11/dist-packages/huggingface_hub/utils/
_auth.py:94: UserWarning:
The secret `HF_TOKEN` does not exist in your Colab secrets.
To authenticate with the Hugging Face Hub, create a token in your
settings tab (https://huggingface.co/settings/tokens), set it as
secret in your Google Colab and restart your session.
You will be able to reuse this secret in all of your notebooks.
Please note that authentication is recommended but still optional to
access public models or datasets.
  warnings.warn(
```

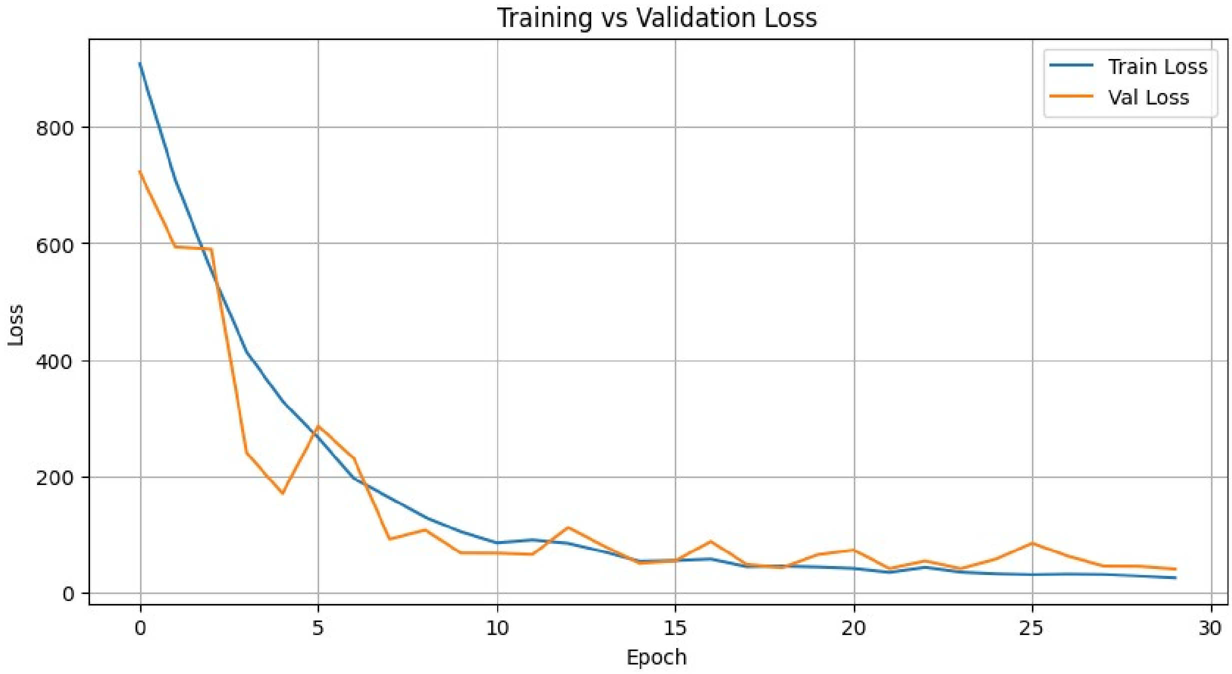
{"model_id":"82c7e5bcfce94e32a08f130a466f34f8","version_major":2,"version_minor":0}

{"model_id":"c00cc80f02494ef9b10a081fe1a8359d","version_major":2,"version_minor":0}

```
Epoch 1/30 – Train Loss: 908.9421, Val Loss: 722.7065
Epoch 2/30 – Train Loss: 709.0007, Val Loss: 593.7569
Epoch 3/30 – Train Loss: 553.4508, Val Loss: 589.9930
Epoch 4/30 – Train Loss: 413.0340, Val Loss: 239.5270
Epoch 5/30 – Train Loss: 328.7163, Val Loss: 169.8787
Epoch 6/30 – Train Loss: 265.9275, Val Loss: 285.9734
Epoch 7/30 – Train Loss: 195.6712, Val Loss: 230.0315
Epoch 8/30 – Train Loss: 162.6000, Val Loss: 91.3099
Epoch 9/30 – Train Loss: 128.9918, Val Loss: 106.8608
Epoch 10/30 – Train Loss: 103.8832, Val Loss: 67.4575
Epoch 11/30 – Train Loss: 85.0553, Val Loss: 67.1922
Epoch 12/30 – Train Loss: 89.9729, Val Loss: 64.9417
Epoch 13/30 – Train Loss: 84.2331, Val Loss: 111.3981
Epoch 14/30 – Train Loss: 69.6312, Val Loss: 79.5981
Epoch 15/30 – Train Loss: 53.1923, Val Loss: 49.7253
Epoch 16/30 – Train Loss: 54.4981, Val Loss: 53.9991
Epoch 17/30 – Train Loss: 57.0512, Val Loss: 87.4989
Epoch 18/30 – Train Loss: 44.1860, Val Loss: 47.9772
Epoch 19/30 – Train Loss: 45.1420, Val Loss: 42.4357
Epoch 20/30 – Train Loss: 43.6117, Val Loss: 64.5994
Epoch 21/30 – Train Loss: 41.1605, Val Loss: 72.6739
Epoch 22/30 – Train Loss: 34.4983, Val Loss: 40.9193
Epoch 23/30 – Train Loss: 43.0455, Val Loss: 53.7844
Epoch 24/30 – Train Loss: 34.9227, Val Loss: 40.8575
Epoch 25/30 – Train Loss: 31.9171, Val Loss: 57.2890
Epoch 26/30 – Train Loss: 30.4219, Val Loss: 84.4559
Epoch 27/30 – Train Loss: 31.3880, Val Loss: 62.1410
Epoch 28/30 – Train Loss: 30.7140, Val Loss: 45.1399
Epoch 29/30 – Train Loss: 27.9249, Val Loss: 44.8089
Epoch 30/30 – Train Loss: 24.4952, Val Loss: 40.1350
```

Training Loss Visualization

```
plt.figure(figsize=(10,5))
plt.plot(train_losses, label="Train Loss")
plt.plot(val_losses, label="Val Loss")
plt.title("Training vs Validation Loss")
plt.xlabel("Epoch")
plt.ylabel("Loss")
plt.legend()
plt.grid(True)
plt.show()
```



Prediction Function (Reusable)

```
def predict_full_map(model, composite_raw, tile_size=128, stride=64):
    model.eval()
    _, H, W = composite_raw.shape
    pred_map = np.zeros((H, W), dtype=np.float32)
    counts = np.zeros((H, W), dtype=np.uint8)

    for i in range(0, H - tile_size + 1, stride):
        for j in range(0, W - tile_size + 1, stride):
            patch = composite_raw[:, i:i+tile_size, j:j+tile_size]
            if np.isnan(patch).any() or patch.shape[1:] != (tile_size,
tile_size):
                continue
            patch_tensor = torch.tensor(patch,
dtype=torch.float32).unsqueeze(0).to(device)
            with torch.no_grad():
                pred = model(patch_tensor).cpu().squeeze().numpy()
            pred_map[i:i+tile_size, j:j+tile_size] += pred
            counts[i:i+tile_size, j:j+tile_size] += 1

    counts[counts == 0] = 1
    return pred_map / counts
```

Predict & Evaluate: Cairo 2023

```
# Load 2023 test data
file_test_X_2023 = os.path.join(base_path,
"Composite_Cairo_2023_Test_cleaned.tif")
file_test_y_2023 = os.path.join(base_path,
"VNL_Cairo_2023_Test_Clipped.tif")

X_test_raw, y_test_raw, meta_2023 = load_and_prepare(file_test_X_2023,
file_test_y_2023)
pred_map_2023 = predict_full_map(model, X_test_raw)

# Save predicted map
meta_2023.update({"count": 1, "dtype": "float32"})
with rio.open("Predicted_Dev_Map_DeepLab_Cairo_2023.tif", "w",
**meta_2023) as dst:
    dst.write(pred_map_2023[np.newaxis, :, :])
```

Advanced Evaluation for Cairo 2023

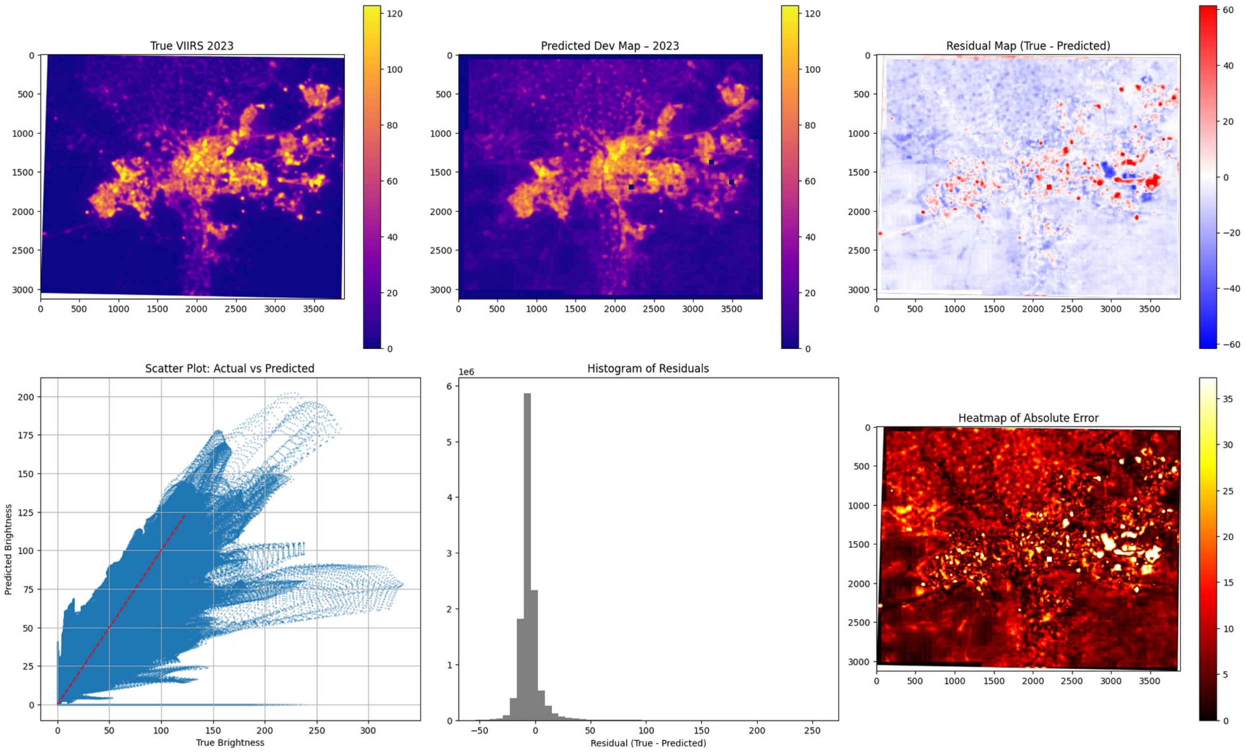
```
# Align shapes
y_true = y_test_raw[:pred_map_2023.shape[0], :pred_map_2023.shape[1]]
y_pred = pred_map_2023
valid_mask = ~np.isnan(y_true)

y_true_flat = y_true[valid_mask]
y_pred_flat = y_pred[valid_mask]

# Standard metrics
mae = mean_absolute_error(y_true_flat, y_pred_flat)
rmse = mean_squared_error(y_true_flat, y_pred_flat)**0.5
```

```
r2 = r2_score(y_true_flat, y_pred_flat)
print(f"□ [Cairo 2023] MAE: {mae:.2f}, RMSE: {rmse:.2f}, R²:
{r2:.4f}")

□ [Cairo 2023] MAE: 8.13, RMSE: 11.31, R²: 0.8207
```

Full Visualization for Cairo 2023

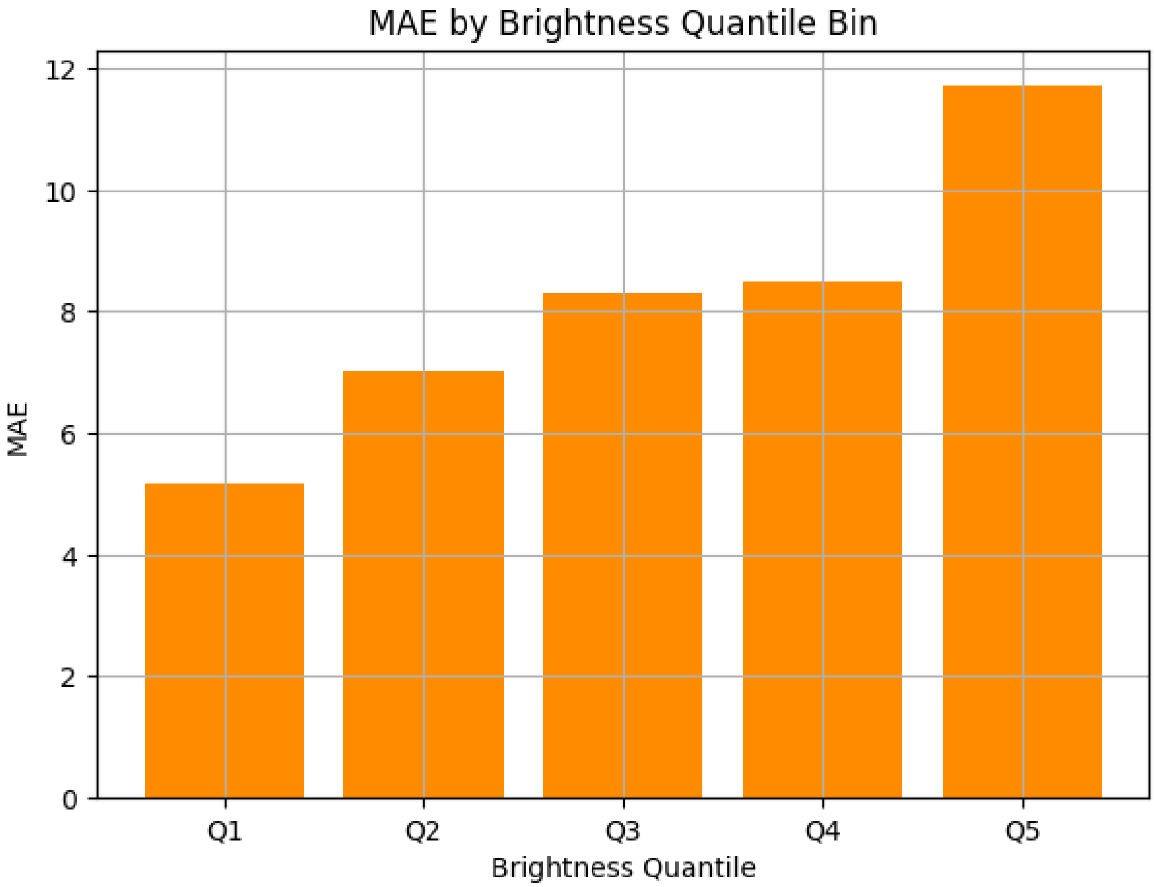
```
vmax = np.nanpercentile(y_true, 99.5)
residuals = y_true - y_pred
abs_error = np.abs(residuals)

plt.figure(figsize=(20, 12))

# True Map
plt.subplot(2, 3, 1)
plt.imshow(y_true, cmap='plasma', vmin=0, vmax=vmax)
plt.title("True VIIRS 2023")
plt.colorbar()

# Predicted Map
plt.subplot(2, 3, 2)
plt.imshow(y_pred, cmap='plasma', vmin=0, vmax=vmax)
plt.title("Predicted Dev Map – 2023")
plt.colorbar()

# Residual Map
plt.subplot(2, 3, 3)
plt.imshow(residuals, cmap='bwr', vmin=-vmax/2, vmax=vmax/2)
plt.title("Residual Map (True - Predicted)")
plt.colorbar()

# Scatter Plot
plt.subplot(2, 3, 4)
plt.scatter(y_true_flat, y_pred_flat, alpha=0.3, s=1)
plt.plot([0, vmax], [0, vmax], 'r--')
plt.xlabel("True Brightness")
plt.ylabel("Predicted Brightness")
plt.title("Scatter Plot: Actual vs Predicted")
plt.grid(True)

# Histogram of Residuals
plt.subplot(2, 3, 5)
plt.hist(residuals[valid_mask].flatten(), bins=50, color='gray')
plt.title("Histogram of Residuals")
plt.xlabel("Residual (True - Predicted)")

# Absolute Error Heatmap
```

```
plt.subplot(2, 3, 6)
plt.imshow(abs_error, cmap='hot', vmin=0,
vmax=np.nanpercentile(abs_error, 99))
plt.title("Heatmap of Absolute Error")
plt.colorbar()

plt.tight_layout()
plt.show()
```



Quantile Bin Comparison

```
bins = np.nanpercentile(y_true_flat, [0, 20, 40, 60, 80, 100])
labels = ["Q1", "Q2", "Q3", "Q4", "Q5"]
digitized = np.digitize(y_true_flat, bins) - 1

bin_mae = [mean_absolute_error(y_true_flat[digitized == i],
y_pred_flat[digitized == i]) for i in range(5)]

plt.figure(figsize=(7, 5))
plt.bar(labels, bin_mae, color='darkorange')
plt.title("MAE by Brightness Quantile Bin")
plt.xlabel("Brightness Quantile")
plt.ylabel("MAE")
plt.grid(True)
plt.show()
```

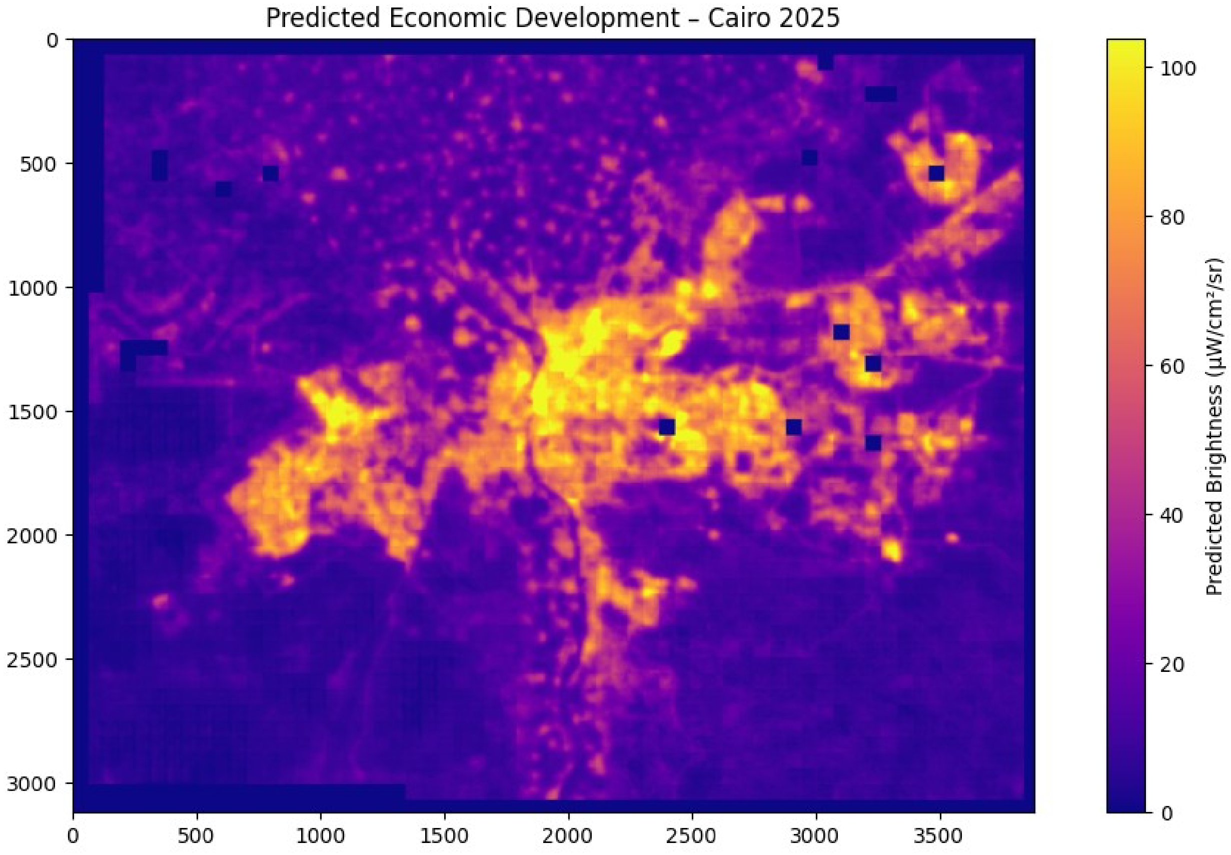


Cairo 2025 – Future Prediction

```
# Load 2025 data (no VNL available)
file_pred_X_2025 = os.path.join(base_path,
"Composite_Cairo_2025_Prediction_cleaned.tif")
X_pred_2025_raw, _, meta_2025 = load_and_prepare(file_pred_X_2025,
None)

# Predict future development
pred_map_2025 = predict_full_map(model, X_pred_2025_raw)

# Save predicted map
meta_2025.update({"count": 1, "dtype": "float32"})
with rio.open("Predicted_Dev_Map_DeepLab_Cairo_2025.tif", "w",
**meta_2025) as dst:
    dst.write(pred_map_2025[np.newaxis, :, :])
```

Visualize Predicted Economic Development – Cairo 2025

```
vmax_2025 = np.nanpercentile(pred_map_2025, 99.5)

plt.figure(figsize=(10, 6))
plt.imshow(pred_map_2025, cmap="plasma", vmin=0, vmax=vmax_2025)
plt.colorbar(label="Predicted Brightness (µW/cm²/sr)")
plt.title("Predicted Economic Development – Cairo 2025")
plt.tight_layout()
plt.show()
```


Predicted Economic Development – Cairo 2025
0
500
1000
1500
2000
2500
3000
0
500
1000
1500
2000
2500
3000
3500
100
80
60
40
20
0
Predicted Brightness (µW/cm²/sr)

Predict & Evaluate: Cairo 2015

```
# Load 2015 data
file_test_X_2015 = os.path.join(base_path,
"Composite_Cairo_2015_cleaned.tif")
file_test_y_2015 = os.path.join(base_path, "VNL_Cairo_2015_Final.tif")

X_test_2015_raw, y_test_2015_raw, meta_2015 =
load_and_prepare(file_test_X_2015, file_test_y_2015)
pred_map_2015 = predict_full_map(model, X_test_2015_raw)

# Save prediction
meta_2015.update({"count": 1, "dtype": "float32"})
with rio.open("Predicted_Dev_Map_DeepLab_Cairo_2015.tif", "w",
**meta_2015) as dst:
    dst.write(pred_map_2015[np.newaxis, :, :])
```

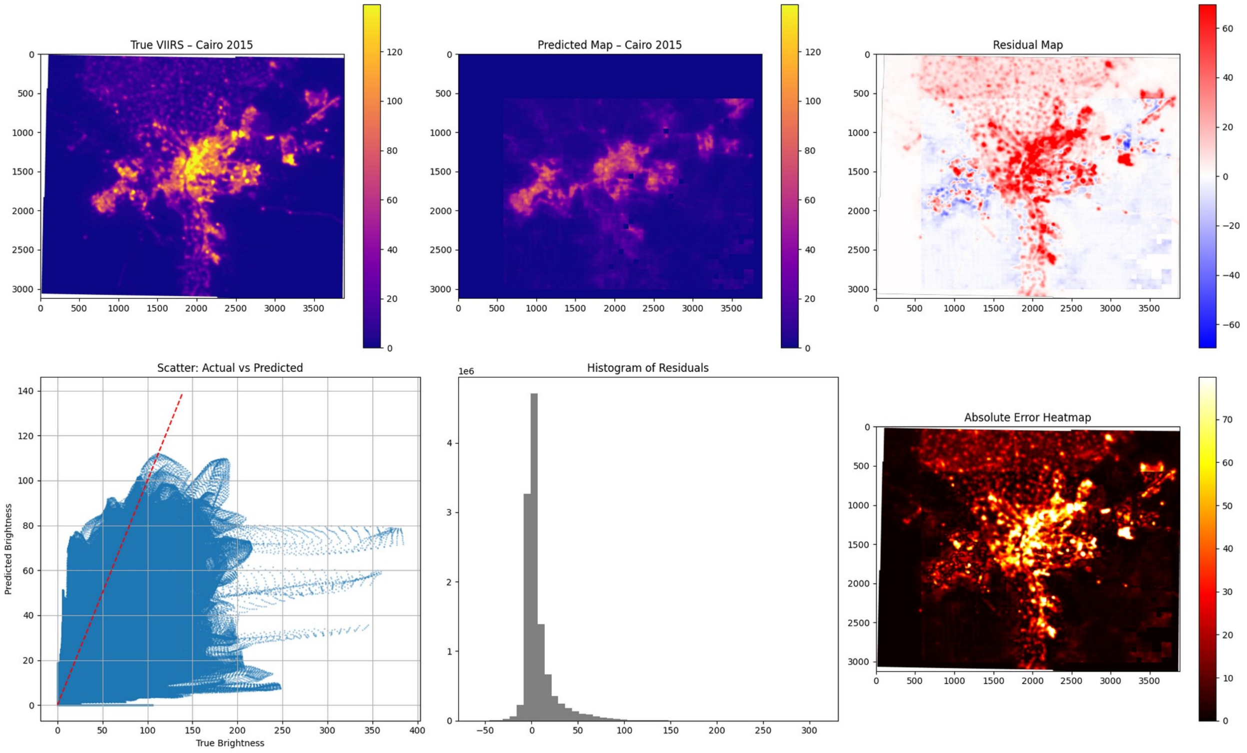
Full Evaluation for Cairo 2015

```
# Align shapes
y_true_2015 =
y_test_2015_raw[:pred_map_2015.shape[0], :pred_map_2015.shape[1]]
y_pred_2015 = pred_map_2015
valid_mask = ~np.isnan(y_true_2015)

y_true_flat = y_true_2015[valid_mask]
y_pred_flat = y_pred_2015[valid_mask]

# Metrics
mae_2015 = mean_absolute_error(y_true_flat, y_pred_flat)
rmse_2015 = mean_squared_error(y_true_flat, y_pred_flat)**0.5
r2_2015 = r2_score(y_true_flat, y_pred_flat)
print(f"□ [Cairo 2015] MAE: {mae_2015:.2f}, RMSE: {rmse_2015:.2f}, R²:
{r2_2015:.4f}")
```

```
□ [Cairo 2015] MAE: 9.11, RMSE: 18.71, R²: 0.4709
```

Visual Analysis for Cairo 2015

```
vmax_2015 = np.nanpercentile(y_true_2015, 99.5)
residuals_2015 = y_true_2015 - y_pred_2015
abs_error_2015 = np.abs(residuals_2015)

plt.figure(figsize=(20, 12))

# True VIIRS
plt.subplot(2, 3, 1)
plt.imshow(y_true_2015, cmap='plasma', vmin=0, vmax=vmax_2015)
plt.title("True VIIRS – Cairo 2015")
plt.colorbar()

# Predicted Map
plt.subplot(2, 3, 2)
plt.imshow(y_pred_2015, cmap='plasma', vmin=0, vmax=vmax_2015)
plt.title("Predicted Map – Cairo 2015")
plt.colorbar()

# Residual Map
plt.subplot(2, 3, 3)
plt.imshow(residuals_2015, cmap='bwr', vmin=-vmax_2015/2,
vmax=vmax_2015/2)
plt.title("Residual Map")
plt.colorbar()

# Scatter Plot
plt.subplot(2, 3, 4)
plt.scatter(y_true_flat, y_pred_flat, alpha=0.3, s=1)
plt.plot([0, vmax_2015], [0, vmax_2015], 'r--')
plt.title("Scatter: Actual vs Predicted")
plt.xlabel("True Brightness")
plt.ylabel("Predicted Brightness")
plt.grid(True)

# Histogram
plt.subplot(2, 3, 5)
plt.hist(residuals_2015[valid_mask].flatten(), bins=50, color='gray')
plt.title("Histogram of Residuals")

# Error Heatmap
plt.subplot(2, 3, 6)
plt.imshow(abs_error_2015, cmap='hot', vmin=0,
vmax=np.nanpercentile(abs_error_2015, 99))
plt.title("Absolute Error Heatmap")
plt.colorbar()

plt.tight_layout()
plt.show()
```



```
# Save model weights
torch.save(model.state_dict(), "DeepLabV3Plus_Cairo2021_Weights.pth")
print("□ Model weights saved to DeepLabV3Plus_Cairo2021_Weights.pth")

□ Model weights saved to DeepLabV3Plus_Cairo2021_Weights.pth
```

Predict & Evaluate: Cairo 2018

```
# Load 2018 data
file_test_X_2018 = os.path.join(base_path,
"Composite_Cairo_2018_cleaned.tif")
file_test_y_2018 = os.path.join(base_path, "VNL_Cairo_2018_Final.tif")

X_test_2018_raw, y_test_2018_raw, meta_2018 =
load_and_prepare(file_test_X_2018, file_test_y_2018)
pred_map_2018 = predict_full_map(model, X_test_2018_raw)

# Save predicted map
meta_2018.update({"count": 1, "dtype": "float32"})
with rio.open("Predicted_Dev_Map_DeepLab_Cairo_2018.tif", "w",
**meta_2018) as dst:
    dst.write(pred_map_2018[np.newaxis, :, :])
```

Evaluation for Cairo 2018

```
# Align and mask
y_true_2018 =
y_test_2018_raw[:pred_map_2018.shape[0], :pred_map_2018.shape[1]]
y_pred_2018 = pred_map_2018
valid_mask = ~np.isnan(y_true_2018)

y_true_flat = y_true_2018[valid_mask]
y_pred_flat = y_pred_2018[valid_mask]

# Metrics
mae_2018 = mean_absolute_error(y_true_flat, y_pred_flat)
rmse_2018 = mean_squared_error(y_true_flat, y_pred_flat)**0.5
r2_2018 = r2_score(y_true_flat, y_pred_flat)
print(f"□ [Cairo 2018] MAE: {mae_2018:.2f}, RMSE: {rmse_2018:.2f}, R²:
{r2_2018:.4f}")
```

Visuals for Cairo 2018

```
vmax_2018 = np.nanpercentile(y_true_2018, 99.5)
residuals_2018 = y_true_2018 - y_pred_2018
abs_error_2018 = np.abs(residuals_2018)

plt.figure(figsize=(20, 12))

plt.subplot(2, 3, 1)
plt.imshow(y_true_2018, cmap='plasma', vmin=0, vmax=vmax_2018)
plt.title("True VIIRS – Cairo 2018")
plt.colorbar()

plt.subplot(2, 3, 2)
plt.imshow(y_pred_2018, cmap='plasma', vmin=0, vmax=vmax_2018)
plt.title("Predicted Map – Cairo 2018")
plt.colorbar()

plt.subplot(2, 3, 3)
plt.imshow(residuals_2018, cmap='bwr', vmin=-vmax_2018/2,
vmax=vmax_2018/2)
plt.title("Residual Map")
plt.colorbar()

plt.subplot(2, 3, 4)
plt.scatter(y_true_flat, y_pred_flat, alpha=0.3, s=1)
plt.plot([0, vmax_2018], [0, vmax_2018], 'r--')
plt.title("Scatter: Actual vs Predicted")
plt.grid(True)
```

```python
plt.subplot(2, 3, 5)
plt.hist(residuals_2018[valid_mask].flatten(), bins=50, color='gray')
plt.title("Histogram of Residuals")

plt.subplot(2, 3, 6)
plt.imshow(abs_error_2018, cmap='hot', vmin=0,
vmax=np.nanpercentile(abs_error_2018, 99))
plt.title("Absolute Error Heatmap")
plt.colorbar()

plt.tight_layout()
plt.show()

# 1. Re-import libraries and re-initialize the model
import segmentation_models_pytorch as smp
import torch

device = torch.device("cuda" if torch.cuda.is_available() else "cpu")

model = smp.DeepLabV3Plus(
    encoder_name="resnet34",
    encoder_weights="imagenet",  # or None if you're running offline
    in_channels=12,
    classes=1,
    activation=None
).to(device)

# 2. Load trained weights
model.load_state_dict(torch.load("DeepLabV3Plus_Cairo2021_Weights.pth"
))
model.eval()  # Important for inference
```

```
/usr/local/lib/python3.11/dist-packages/huggingface_hub/utils/
_auth.py:94: UserWarning:
The secret `HF_TOKEN` does not exist in your Colab secrets.
To authenticate with the Hugging Face Hub, create a token in your
settings tab (https://huggingface.co/settings/tokens), set it as
secret in your Google Colab and restart your session.
You will be able to reuse this secret in all of your notebooks.
Please note that authentication is recommended but still optional to
access public models or datasets.
  warnings.warn(
```

```
{"model_id":"e2ed906edc6146d1ae6b649fb0baf780","version_major":2,"vers
ion_minor":0}

{"model_id":"75e2575ceb5249d6b02695cfdbcca830","version_major":2,"vers
ion_minor":0}
```

```
DeepLabV3Plus(
  (encoder): ResNetEncoder(
    (conv1): Conv2d(12, 64, kernel_size=(7, 7), stride=(2, 2),
padding=(3, 3), bias=False)
    (bn1): BatchNorm2d(64, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
    (relu): ReLU(inplace=True)
    (maxpool): MaxPool2d(kernel_size=3, stride=2, padding=1,
dilation=1, ceil_mode=False)
    (layer1): Sequential(
      (0): BasicBlock(
        (conv1): Conv2d(64, 64, kernel_size=(3, 3), stride=(1, 1),
padding=(1, 1), bias=False)
        (bn1): BatchNorm2d(64, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
        (relu): ReLU(inplace=True)
        (conv2): Conv2d(64, 64, kernel_size=(3, 3), stride=(1, 1),
padding=(1, 1), bias=False)
        (bn2): BatchNorm2d(64, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
      )
      (1): BasicBlock(
        (conv1): Conv2d(64, 64, kernel_size=(3, 3), stride=(1, 1),
padding=(1, 1), bias=False)
        (bn1): BatchNorm2d(64, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
        (relu): ReLU(inplace=True)
        (conv2): Conv2d(64, 64, kernel_size=(3, 3), stride=(1, 1),
padding=(1, 1), bias=False)
        (bn2): BatchNorm2d(64, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
      )
      (2): BasicBlock(
        (conv1): Conv2d(64, 64, kernel_size=(3, 3), stride=(1, 1),
padding=(1, 1), bias=False)
        (bn1): BatchNorm2d(64, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
        (relu): ReLU(inplace=True)
        (conv2): Conv2d(64, 64, kernel_size=(3, 3), stride=(1, 1),
padding=(1, 1), bias=False)
        (bn2): BatchNorm2d(64, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
      )
    )
    (layer2): Sequential(
      (0): BasicBlock(
        (conv1): Conv2d(64, 128, kernel_size=(3, 3), stride=(2, 2),
padding=(1, 1), bias=False)
        (bn1): BatchNorm2d(128, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
        (relu): ReLU(inplace=True)
        (conv2): Conv2d(128, 128, kernel_size=(3, 3), stride=(1, 1),
padding=(1, 1), bias=False)
        (bn2): BatchNorm2d(128, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
        (downsample): Sequential(
          (0): Conv2d(64, 128, kernel_size=(1, 1), stride=(2, 2),
bias=False)
          (1): BatchNorm2d(128, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
        )
      )
      (1): BasicBlock(
        (conv1): Conv2d(128, 128, kernel_size=(3, 3), stride=(1, 1),
padding=(1, 1), bias=False)
        (bn1): BatchNorm2d(128, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
        (relu): ReLU(inplace=True)
        (conv2): Conv2d(128, 128, kernel_size=(3, 3), stride=(1, 1),
padding=(1, 1), bias=False)
        (bn2): BatchNorm2d(128, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
      )
      (2): BasicBlock(
        (conv1): Conv2d(128, 128, kernel_size=(3, 3), stride=(1, 1),
padding=(1, 1), bias=False)
        (bn1): BatchNorm2d(128, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
        (relu): ReLU(inplace=True)
        (conv2): Conv2d(128, 128, kernel_size=(3, 3), stride=(1, 1),
padding=(1, 1), bias=False)
        (bn2): BatchNorm2d(128, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
      )
      (3): BasicBlock(
        (conv1): Conv2d(128, 128, kernel_size=(3, 3), stride=(1, 1),
padding=(1, 1), bias=False)
        (bn1): BatchNorm2d(128, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
        (relu): ReLU(inplace=True)
        (conv2): Conv2d(128, 128, kernel_size=(3, 3), stride=(1, 1),
padding=(1, 1), bias=False)
        (bn2): BatchNorm2d(128, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
      )
    )
    (layer3): Sequential(
      (0): BasicBlock(
        (conv1): Conv2d(128, 256, kernel_size=(3, 3), stride=(2, 2),
padding=(1, 1), bias=False)
```

```
        (bn1): BatchNorm2d(256, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
        (relu): ReLU(inplace=True)
        (conv2): Conv2d(256, 256, kernel_size=(3, 3), stride=(1, 1),
padding=(1, 1), bias=False)
        (bn2): BatchNorm2d(256, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
        (downsample): Sequential(
          (0): Conv2d(128, 256, kernel_size=(1, 1), stride=(2, 2),
bias=False)
          (1): BatchNorm2d(256, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
        )
      )
      (1): BasicBlock(
        (conv1): Conv2d(256, 256, kernel_size=(3, 3), stride=(1, 1),
padding=(1, 1), bias=False)
        (bn1): BatchNorm2d(256, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
        (relu): ReLU(inplace=True)
        (conv2): Conv2d(256, 256, kernel_size=(3, 3), stride=(1, 1),
padding=(1, 1), bias=False)
        (bn2): BatchNorm2d(256, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
      )
      (2): BasicBlock(
        (conv1): Conv2d(256, 256, kernel_size=(3, 3), stride=(1, 1),
padding=(1, 1), bias=False)
        (bn1): BatchNorm2d(256, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
        (relu): ReLU(inplace=True)
        (conv2): Conv2d(256, 256, kernel_size=(3, 3), stride=(1, 1),
padding=(1, 1), bias=False)
        (bn2): BatchNorm2d(256, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
      )
      (3): BasicBlock(
        (conv1): Conv2d(256, 256, kernel_size=(3, 3), stride=(1, 1),
padding=(1, 1), bias=False)
        (bn1): BatchNorm2d(256, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
        (relu): ReLU(inplace=True)
        (conv2): Conv2d(256, 256, kernel_size=(3, 3), stride=(1, 1),
padding=(1, 1), bias=False)
        (bn2): BatchNorm2d(256, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
      )
      (4): BasicBlock(
        (conv1): Conv2d(256, 256, kernel_size=(3, 3), stride=(1, 1),
padding=(1, 1), bias=False)
        (bn1): BatchNorm2d(256, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
        (relu): ReLU(inplace=True)
        (conv2): Conv2d(256, 256, kernel_size=(3, 3), stride=(1, 1),
padding=(1, 1), bias=False)
        (bn2): BatchNorm2d(256, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
      )
      (5): BasicBlock(
        (conv1): Conv2d(256, 256, kernel_size=(3, 3), stride=(1, 1),
padding=(1, 1), bias=False)
        (bn1): BatchNorm2d(256, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
        (relu): ReLU(inplace=True)
        (conv2): Conv2d(256, 256, kernel_size=(3, 3), stride=(1, 1),
padding=(1, 1), bias=False)
        (bn2): BatchNorm2d(256, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
      )
    )
    (layer4): Sequential(
      (0): BasicBlock(
        (conv1): Conv2d(256, 512, kernel_size=(3, 3), stride=(1, 1),
padding=(2, 2), dilation=(2, 2), bias=False)
        (bn1): BatchNorm2d(512, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
        (relu): ReLU(inplace=True)
        (conv2): Conv2d(512, 512, kernel_size=(3, 3), stride=(1, 1),
padding=(2, 2), dilation=(2, 2), bias=False)
        (bn2): BatchNorm2d(512, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
        (downsample): Sequential(
          (0): Conv2d(256, 512, kernel_size=(1, 1), stride=(1, 1),
dilation=(2, 2), bias=False)
          (1): BatchNorm2d(512, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
        )
      )
      (1): BasicBlock(
        (conv1): Conv2d(512, 512, kernel_size=(3, 3), stride=(1, 1),
padding=(2, 2), dilation=(2, 2), bias=False)
        (bn1): BatchNorm2d(512, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
        (relu): ReLU(inplace=True)
        (conv2): Conv2d(512, 512, kernel_size=(3, 3), stride=(1, 1),
padding=(2, 2), dilation=(2, 2), bias=False)
        (bn2): BatchNorm2d(512, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
```

```
      )
      (2): BasicBlock(
        (conv1): Conv2d(512, 512, kernel_size=(3, 3), stride=(1, 1),
padding=(2, 2), dilation=(2, 2), bias=False)
        (bn1): BatchNorm2d(512, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
        (relu): ReLU(inplace=True)
        (conv2): Conv2d(512, 512, kernel_size=(3, 3), stride=(1, 1),
padding=(2, 2), dilation=(2, 2), bias=False)
        (bn2): BatchNorm2d(512, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
      )
    )
  )
  (decoder): DeepLabV3PlusDecoder(
    (aspp): Sequential(
      (0): ASPP(
        (convs): ModuleList(
          (0): Sequential(
            (0): Conv2d(512, 256, kernel_size=(1, 1), stride=(1, 1),
bias=False)
            (1): BatchNorm2d(256, eps=1e-05, momentum=0.1,
affine=True, track_running_stats=True)
            (2): ReLU()
          )
          (1): ASPPSeparableConv(
            (0): SeparableConv2d(
              (0): Conv2d(512, 512, kernel_size=(3, 3), stride=(1, 1),
padding=(12, 12), dilation=(12, 12), groups=512, bias=False)
              (1): Conv2d(512, 256, kernel_size=(1, 1), stride=(1, 1),
bias=False)
            )
            (1): BatchNorm2d(256, eps=1e-05, momentum=0.1,
affine=True, track_running_stats=True)
            (2): ReLU()
          )
          (2): ASPPSeparableConv(
            (0): SeparableConv2d(
              (0): Conv2d(512, 512, kernel_size=(3, 3), stride=(1, 1),
padding=(24, 24), dilation=(24, 24), groups=512, bias=False)
              (1): Conv2d(512, 256, kernel_size=(1, 1), stride=(1, 1),
bias=False)
            )
            (1): BatchNorm2d(256, eps=1e-05, momentum=0.1,
affine=True, track_running_stats=True)
            (2): ReLU()
          )
          (3): ASPPSeparableConv(
            (0): SeparableConv2d(
              (0): Conv2d(512, 512, kernel_size=(3, 3), stride=(1, 1),
padding=(36, 36), dilation=(36, 36), groups=512, bias=False)
              (1): Conv2d(512, 256, kernel_size=(1, 1), stride=(1, 1),
bias=False)
            )
            (1): BatchNorm2d(256, eps=1e-05, momentum=0.1,
affine=True, track_running_stats=True)
            (2): ReLU()
          )
          (4): ASPPPooling(
            (0): AdaptiveAvgPool2d(output_size=1)
            (1): Conv2d(512, 256, kernel_size=(1, 1), stride=(1, 1),
bias=False)
            (2): BatchNorm2d(256, eps=1e-05, momentum=0.1,
affine=True, track_running_stats=True)
            (3): ReLU()
          )
        )
        (project): Sequential(
          (0): Conv2d(1280, 256, kernel_size=(1, 1), stride=(1, 1),
bias=False)
          (1): BatchNorm2d(256, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
          (2): ReLU()
          (3): Dropout(p=0.5, inplace=False)
        )
      )
      (1): SeparableConv2d(
        (0): Conv2d(256, 256, kernel_size=(3, 3), stride=(1, 1),
padding=(1, 1), groups=256, bias=False)
        (1): Conv2d(256, 256, kernel_size=(1, 1), stride=(1, 1),
bias=False)
      )
      (2): BatchNorm2d(256, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
      (3): ReLU()
    )
    (up): UpsamplingBilinear2d(scale_factor=4.0, mode='bilinear')
    (block1): Sequential(
      (0): Conv2d(64, 48, kernel_size=(1, 1), stride=(1, 1),
bias=False)
      (1): BatchNorm2d(48, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
      (2): ReLU()
    )
    (block2): Sequential(
      (0): SeparableConv2d(
        (0): Conv2d(304, 304, kernel_size=(3, 3), stride=(1, 1),
padding=(1, 1), groups=304, bias=False)
```

```
        (1): Conv2d(304, 256, kernel_size=(1, 1), stride=(1, 1),
bias=False)
      )
      (1): BatchNorm2d(256, eps=1e-05, momentum=0.1, affine=True,
track_running_stats=True)
      (2): ReLU()
    )
  )
  (segmentation_head): SegmentationHead(
    (0): Conv2d(256, 1, kernel_size=(1, 1), stride=(1, 1))
    (1): UpsamplingBilinear2d(scale_factor=4.0, mode='bilinear')
    (2): Activation(
      (activation): Identity()
    )
  )
)
```

Predict & Evaluate: Cairo 2019

```
# Load 2019 data
file_test_X_2019 = os.path.join(base_path,
"Composite_Cairo_2019_cleaned.tif")
file_test_y_2019 = os.path.join(base_path, "VNL_Cairo_2019_Final.tif")

X_test_2019_raw, y_test_2019_raw, meta_2019 =
load_and_prepare(file_test_X_2019, file_test_y_2019)
pred_map_2019 = predict_full_map(model, X_test_2019_raw)

# Save predicted map
meta_2019.update({"count": 1, "dtype": "float32"})
with rio.open("Predicted_Dev_Map_DeepLab_Cairo_2019.tif", "w",
**meta_2019) as dst:
    dst.write(pred_map_2019[np.newaxis, :, :])
```

Evaluation for Cairo 2019

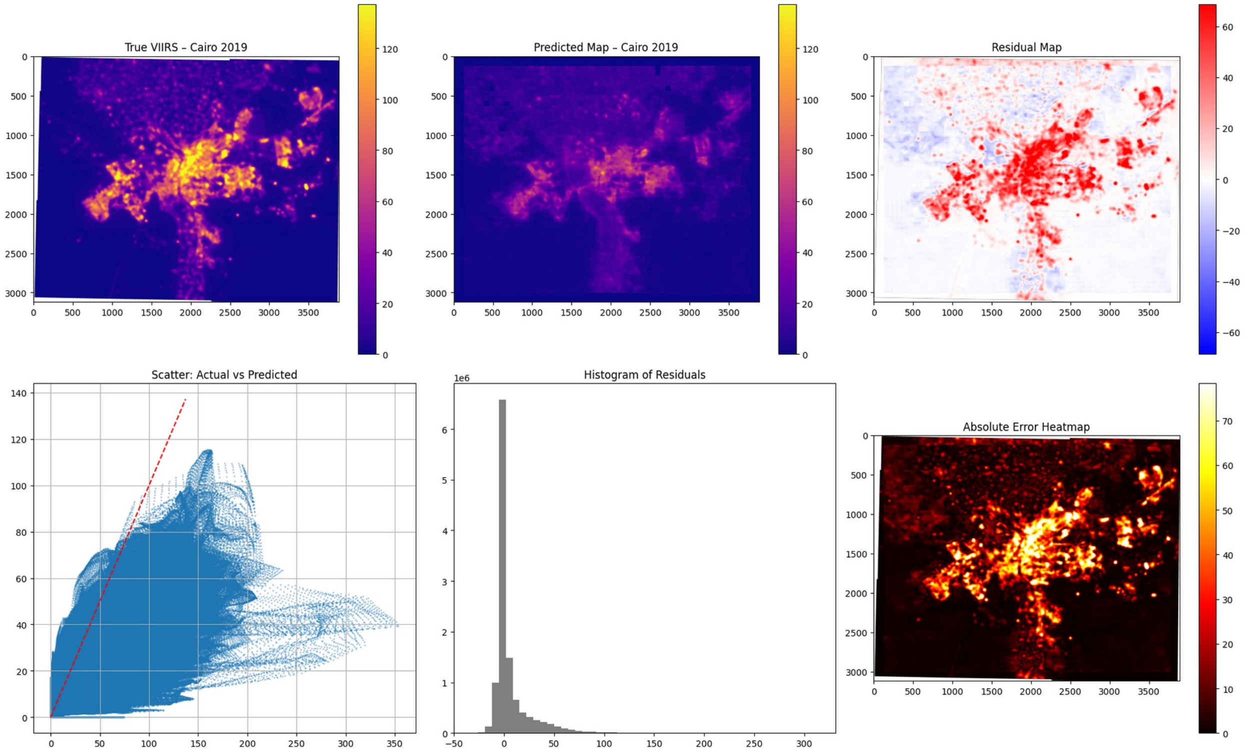
```
# Align and mask
y_true_2019 =
y_test_2019_raw[:pred_map_2019.shape[0], :pred_map_2019.shape[1]]
y_pred_2019 = pred_map_2019
valid_mask = ~np.isnan(y_true_2019)

y_true_flat = y_true_2019[valid_mask]
y_pred_flat = y_pred_2019[valid_mask]

# Metrics
```

```
mae_2019 = mean_absolute_error(y_true_flat, y_pred_flat)
rmse_2019 = mean_squared_error(y_true_flat, y_pred_flat)**0.5
r2_2019 = r2_score(y_true_flat, y_pred_flat)
print(f"□ [Cairo 2019] MAE: {mae_2019:.2f}, RMSE: {rmse_2019:.2f}, R²:
{r2_2019:.4f}")
```

```
□ [Cairo 2019] MAE: 9.20, RMSE: 18.89, R²: 0.5155
```

Visuals for Cairo 2019

```
vmax_2019 = np.nanpercentile(y_true_2019, 99.5)
residuals_2019 = y_true_2019 - y_pred_2019
abs_error_2019 = np.abs(residuals_2019)

plt.figure(figsize=(20, 12))

plt.subplot(2, 3, 1)
plt.imshow(y_true_2019, cmap='plasma', vmin=0, vmax=vmax_2019)
plt.title("True VIIRS — Cairo 2019")
plt.colorbar()

plt.subplot(2, 3, 2)
plt.imshow(y_pred_2019, cmap='plasma', vmin=0, vmax=vmax_2019)
plt.title("Predicted Map — Cairo 2019")
plt.colorbar()

plt.subplot(2, 3, 3)
plt.imshow(residuals_2019, cmap='bwr', vmin=-vmax_2019/2,
vmax=vmax_2019/2)
plt.title("Residual Map")
plt.colorbar()

plt.subplot(2, 3, 4)
plt.scatter(y_true_flat, y_pred_flat, alpha=0.3, s=1)
plt.plot([0, vmax_2019], [0, vmax_2019], 'r--')
plt.title("Scatter: Actual vs Predicted")
plt.grid(True)

plt.subplot(2, 3, 5)
plt.hist(residuals_2019[valid_mask].flatten(), bins=50, color='gray')
plt.title("Histogram of Residuals")

plt.subplot(2, 3, 6)
plt.imshow(abs_error_2019, cmap='hot', vmin=0,
vmax=np.nanpercentile(abs_error_2019, 99))
plt.title("Absolute Error Heatmap")
plt.colorbar()
plt.tight_layout()
plt.show()
```



Predict & Evaluate: Cairo 2020

```
# Load 2020 data
file_test_X_2020 = os.path.join(base_path,
"Composite_Cairo_2020_cleaned.tif")
file_test_y_2020 = os.path.join(base_path, "VNL_Cairo_2020_Final.tif")

X_test_2020_raw, y_test_2020_raw, meta_2020 =
load_and_prepare(file_test_X_2020, file_test_y_2020)
pred_map_2020 = predict_full_map(model, X_test_2020_raw)

# Save predicted map
meta_2020.update({"count": 1, "dtype": "float32"})
with rio.open("Predicted_Dev_Map_DeepLab_Cairo_2020.tif", "w",
**meta_2020) as dst:
    dst.write(pred_map_2020[np.newaxis, :, :])
```

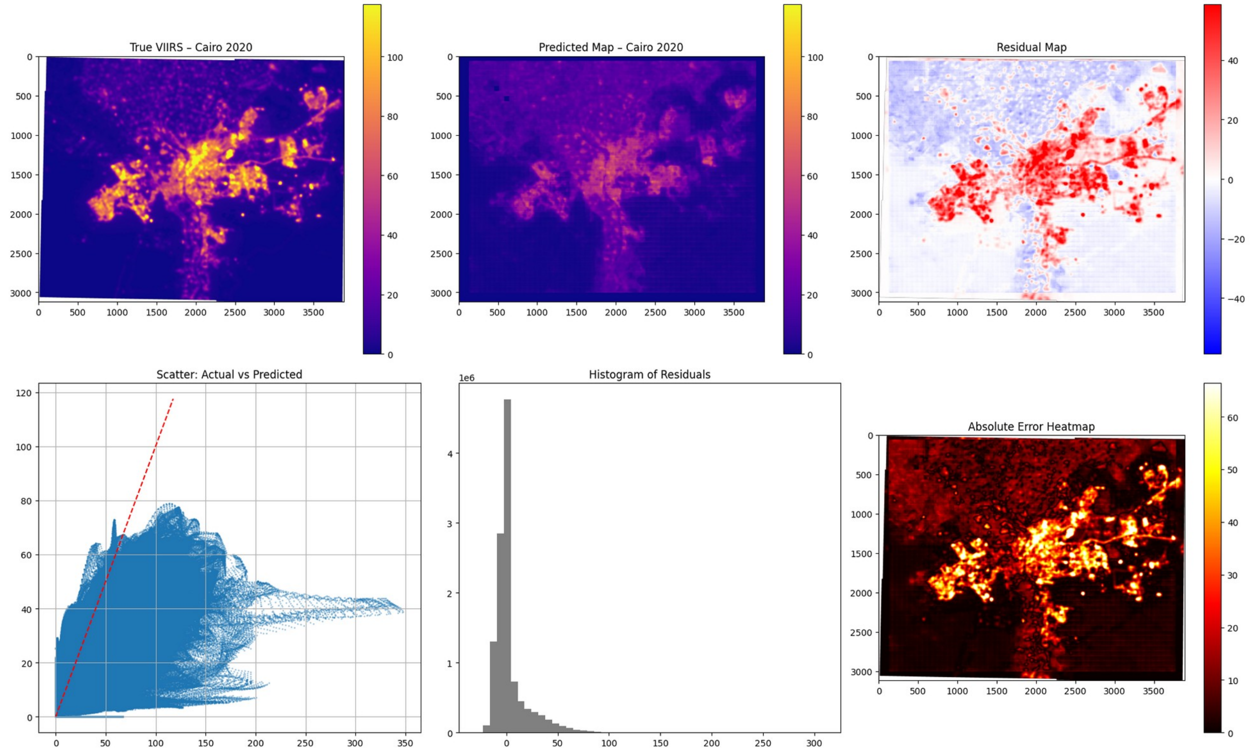
Evaluation for Cairo 2020

```
y_true_2020 =
y_test_2020_raw[:pred_map_2020.shape[0], :pred_map_2020.shape[1]]
y_pred_2020 = pred_map_2020
valid_mask = ~np.isnan(y_true_2020)

y_true_flat = y_true_2020[valid_mask]
y_pred_flat = y_pred_2020[valid_mask]

mae_2020 = mean_absolute_error(y_true_flat, y_pred_flat)
rmse_2020 = mean_squared_error(y_true_flat, y_pred_flat)**0.5
r2_2020 = r2_score(y_true_flat, y_pred_flat)
print(f"□ [Cairo 2020] MAE: {mae_2020:.2f}, RMSE: {rmse_2020:.2f}, R²:
{r2_2020:.4f}")
```

```
□ [Cairo 2020] MAE: 9.25, RMSE: 16.69, R²: 0.5368
```

Visuals for Cairo 2020

```
vmax_2020 = np.nanpercentile(y_true_2020, 99.5)
residuals_2020 = y_true_2020 - y_pred_2020
abs_error_2020 = np.abs(residuals_2020)

plt.figure(figsize=(20, 12))

plt.subplot(2, 3, 1)
plt.imshow(y_true_2020, cmap='plasma', vmin=0, vmax=vmax_2020)
plt.title("True VIIRS – Cairo 2020")
plt.colorbar()

plt.subplot(2, 3, 2)
plt.imshow(y_pred_2020, cmap='plasma', vmin=0, vmax=vmax_2020)
plt.title("Predicted Map – Cairo 2020")
plt.colorbar()

plt.subplot(2, 3, 3)
plt.imshow(residuals_2020, cmap='bwr', vmin=-vmax_2020/2,
vmax=vmax_2020/2)
plt.title("Residual Map")
plt.colorbar()

plt.subplot(2, 3, 4)
plt.scatter(y_true_flat, y_pred_flat, alpha=0.3, s=1)
plt.plot([0, vmax_2020], [0, vmax_2020], 'r--')
plt.title("Scatter: Actual vs Predicted")
plt.grid(True)
plt.subplot(2, 3, 5)
plt.hist(residuals_2020[valid_mask].flatten(), bins=50, color='gray')
plt.title("Histogram of Residuals")

plt.subplot(2, 3, 6)
plt.imshow(abs_error_2020, cmap='hot', vmin=0,
vmax=np.nanpercentile(abs_error_2020, 99))
plt.title("Absolute Error Heatmap")
plt.colorbar()

plt.tight_layout()
plt.show()
```



Predict & Evaluate: Cairo 2022

```
# Load 2022 data
file_test_X_2022 = os.path.join(base_path,
"Composite_Cairo_2022_cleaned.tif")
file_test_y_2022 = os.path.join(base_path, "VNL_Cairo_2022_Final.tif")

X_test_2022_raw, y_test_2022_raw, meta_2022 =
load_and_prepare(file_test_X_2022, file_test_y_2022)
pred_map_2022 = predict_full_map(model, X_test_2022_raw)

# Save predicted map
```

```
meta_2022.update({"count": 1, "dtype": "float32"})
with rio.open("Predicted_Dev_Map_DeepLab_Cairo_2022.tif", "w",
**meta_2022) as dst:
    dst.write(pred_map_2022[np.newaxis, :, :])
```

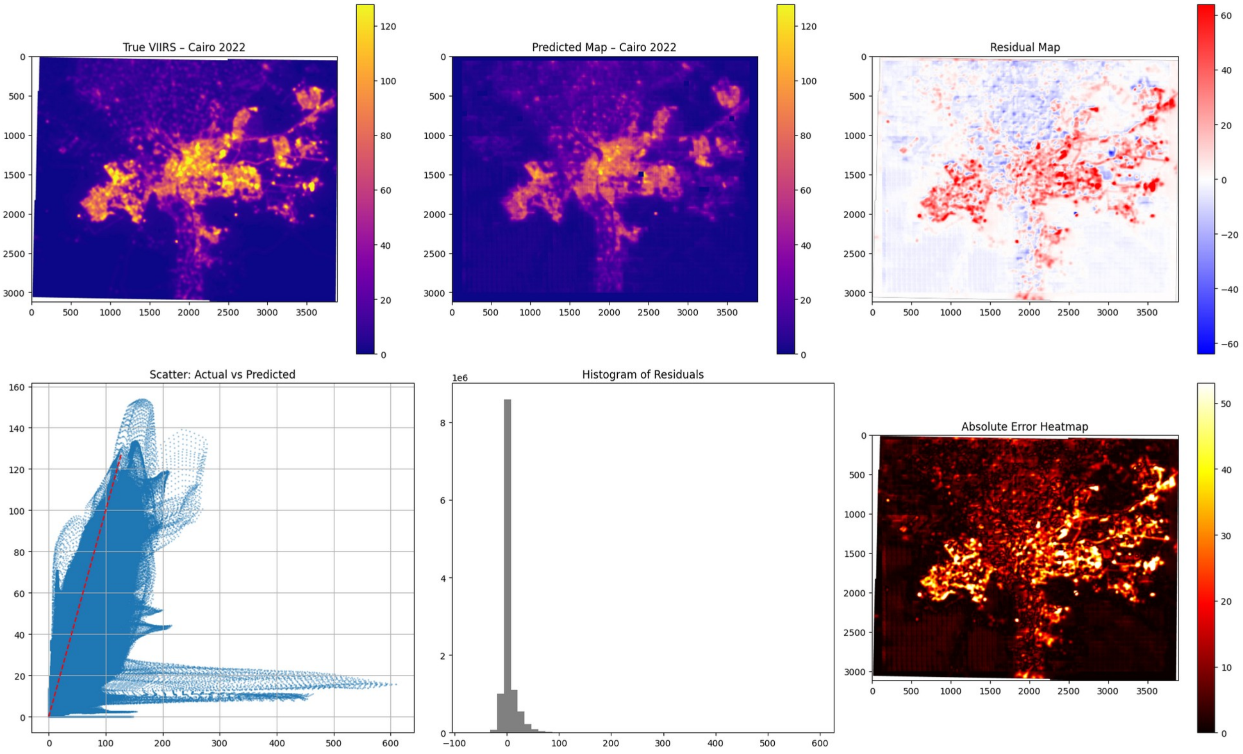
Evaluation for Cairo 2022

```
y_true_2022 =
y_test_2022_raw[:pred_map_2022.shape[0], :pred_map_2022.shape[1]]
y_pred_2022 = pred_map_2022
valid_mask = ~np.isnan(y_true_2022)

y_true_flat = y_true_2022[valid_mask]
y_pred_flat = y_pred_2022[valid_mask]

mae_2022 = mean_absolute_error(y_true_flat, y_pred_flat)
rmse_2022 = mean_squared_error(y_true_flat, y_pred_flat)**0.5
r2_2022 = r2_score(y_true_flat, y_pred_flat)
print(f"□ [Cairo 2022] MAE: {mae_2022:.2f}, RMSE: {rmse_2022:.2f}, R²:
{r2_2022:.4f}")
```

```
□ [Cairo 2022] MAE: 6.78, RMSE: 14.08, R²: 0.7442
```

Visuals for Cairo 2022

```
vmax_2022 = np.nanpercentile(y_true_2022, 99.5)
residuals_2022 = y_true_2022 - y_pred_2022
abs_error_2022 = np.abs(residuals_2022)

plt.figure(figsize=(20, 12))

plt.subplot(2, 3, 1)
plt.imshow(y_true_2022, cmap='plasma', vmin=0, vmax=vmax_2022)
plt.title("True VIIRS – Cairo 2022")
plt.colorbar()

plt.subplot(2, 3, 2)
plt.imshow(y_pred_2022, cmap='plasma', vmin=0, vmax=vmax_2022)
plt.title("Predicted Map – Cairo 2022")
plt.colorbar()

plt.subplot(2, 3, 3)
plt.imshow(residuals_2022, cmap='bwr', vmin=-vmax_2022/2,
vmax=vmax_2022/2)
plt.title("Residual Map")
plt.colorbar()
plt.subplot(2, 3, 4)
plt.scatter(y_true_flat, y_pred_flat, alpha=0.3, s=1)
plt.plot([0, vmax_2022], [0, vmax_2022], 'r--')
plt.title("Scatter: Actual vs Predicted")
plt.grid(True)

plt.subplot(2, 3, 5)
plt.hist(residuals_2022[valid_mask].flatten(), bins=50, color='gray')
plt.title("Histogram of Residuals")

plt.subplot(2, 3, 6)
plt.imshow(abs_error_2022, cmap='hot', vmin=0,
vmax=np.nanpercentile(abs_error_2022, 99))
plt.title("Absolute Error Heatmap")
plt.colorbar()

plt.tight_layout()
plt.show()
```



Predict & Evaluate: Cairo 2024

```
# Load 2024 data
file_test_X_2024 = os.path.join(base_path,
"Composite_Cairo_2024_cleaned.tif")
file_test_y_2024 = os.path.join(base_path, "VNL_Cairo_2024_Final.tif")
```

```
X_test_2024_raw, y_test_2024_raw, meta_2024 =
load_and_prepare(file_test_X_2024, file_test_y_2024)
pred_map_2024 = predict_full_map(model, X_test_2024_raw)

# Save predicted map
meta_2024.update({"count": 1, "dtype": "float32"})
with rio.open("Predicted_Dev_Map_DeepLab_Cairo_2024.tif", "w",
**meta_2024) as dst:
    dst.write(pred_map_2024[np.newaxis, :, :])
```

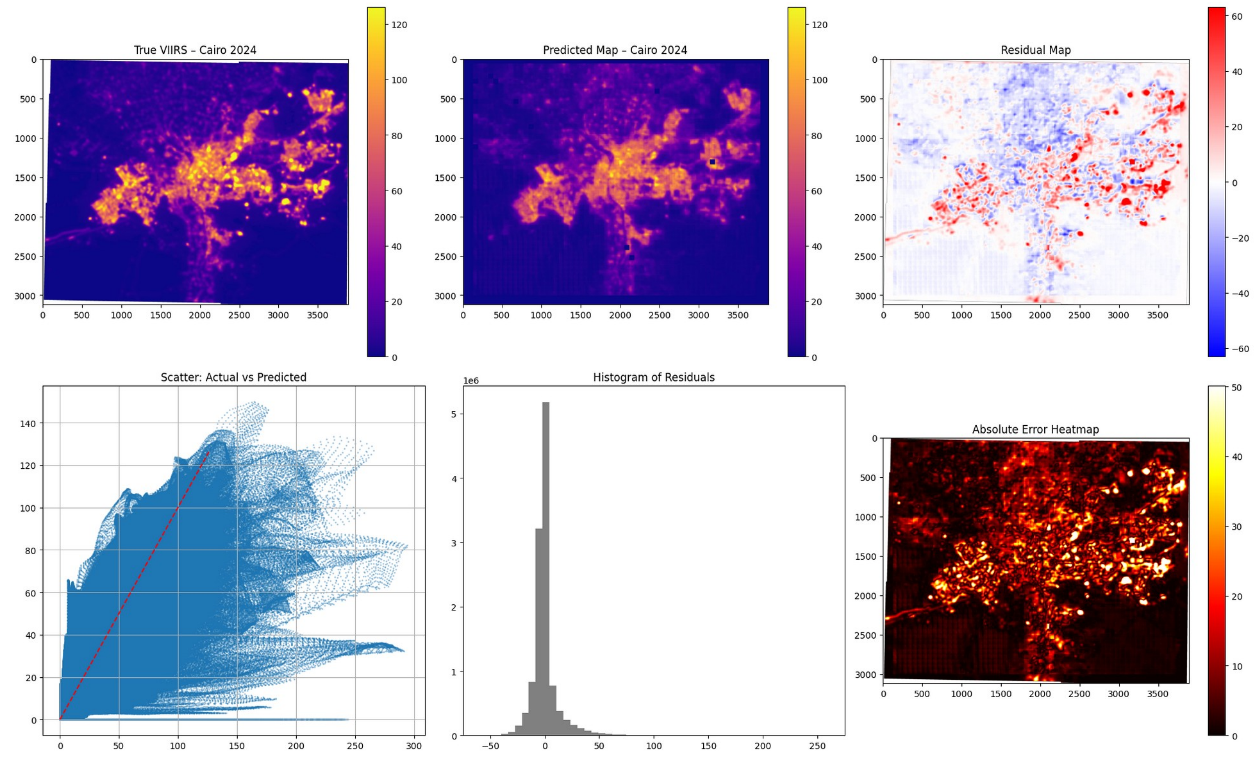
Evaluation for Cairo 2024

```
y_true_2024 =
y_test_2024_raw[:pred_map_2024.shape[0], :pred_map_2024.shape[1]]
y_pred_2024 = pred_map_2024
valid_mask = ~np.isnan(y_true_2024)

y_true_flat = y_true_2024[valid_mask]
y_pred_flat = y_pred_2024[valid_mask]

mae_2024 = mean_absolute_error(y_true_flat, y_pred_flat)
rmse_2024 = mean_squared_error(y_true_flat, y_pred_flat)**0.5
r2_2024 = r2_score(y_true_flat, y_pred_flat)
print(f"□ [Cairo 2024] MAE: {mae_2024:.2f}, RMSE: {rmse_2024:.2f}, R²:
{r2_2024:.4f}")
```

```
□ [Cairo 2024] MAE: 6.68, RMSE: 12.98, R²: 0.7742
```

Visuals for Cairo 2024

```
vmax_2024 = np.nanpercentile(y_true_2024, 99.5)
residuals_2024 = y_true_2024 - y_pred_2024
abs_error_2024 = np.abs(residuals_2024)

plt.figure(figsize=(20, 12))

plt.subplot(2, 3, 1)
plt.imshow(y_true_2024, cmap='plasma', vmin=0, vmax=vmax_2024)
plt.title("True VIIRS – Cairo 2024")
plt.colorbar()

plt.subplot(2, 3, 2)
plt.imshow(y_pred_2024, cmap='plasma', vmin=0, vmax=vmax_2024)
plt.title("Predicted Map – Cairo 2024")
plt.colorbar()
plt.subplot(2, 3, 3)
plt.imshow(residuals_2024, cmap='bwr', vmin=-vmax_2024/2,
vmax=vmax_2024/2)
plt.title("Residual Map")
plt.colorbar()

plt.subplot(2, 3, 4)
plt.scatter(y_true_flat, y_pred_flat, alpha=0.3, s=1)
plt.plot([0, vmax_2024], [0, vmax_2024], 'r--')
plt.title("Scatter: Actual vs Predicted")
plt.grid(True)

plt.subplot(2, 3, 5)
plt.hist(residuals_2024[valid_mask].flatten(), bins=50, color='gray')
plt.title("Histogram of Residuals")

plt.subplot(2, 3, 6)
plt.imshow(abs_error_2024, cmap='hot', vmin=0,
vmax=np.nanpercentile(abs_error_2024, 99))
plt.title("Absolute Error Heatmap")
plt.colorbar()

plt.tight_layout()
plt.show()
```



Export Table to CSV

```
df_metrics.to_csv("Cairo_Prediction_Metrics_Summary.csv", index=False)
```